Integrated strategies for wild oat (*Avena* spp.) management in southern Australian farming systems

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Abstract

Wild oats (*Avena* spp.) are one of the most widespread and important weeds of southern Australian farming systems. They have also developed resistance to the Acetyl Coenzyme A Carboxylase (ACCase) inhibiting herbicides, further ensuring their persistence. A study was undertaken to determine the occurrence and species incidence of wild oats in a major cropping region of southern Australia. It was found that 90% of cropping paddocks in the mid-north of South Australia contained wild oats, with two species, *A. fatua* and *A. ludoviciana* proliferating in varying proportions. Wild oat seed samples were also screened for resistance to the ACCase inhibiting herbicide, diclofop-methyl, with 2.3% of paddocks exhibiting an agronomically relevant level of resistance.

Population dynamics studies were undertaken at two sites to define the seed bank decline and emergence pattern of several wild oat populations over a three year period. At both sites, seed bank decline followed an exponential pattern, with the greatest loss occurring in the first year (56-81%). Wild oats demonstrated an extended emergence habit, a characteristic which makes the prevention of in-crop seed production difficult.

Management studies were conducted to determine appropriate strategies for the control of wild oats in southern Australian farming systems. The techniques included the burning of cereal crop residues and flamprop-*m*-methyl as a late applied post emergent herbicide treatment. It was determined that viable wild oat seeds on the soil surface can be reduced through the burning of crop residues, with control ranging from 48 to 98%. Furthermore, stubble burning can stimulate plant emergence of those wild oat seeds that survived a burn. Alternative experiments determined that the timing of flamprop-*m*-methyl application was critical in controlling numbers of seed produced from wild oat plants. Application at the early tiller elongation stage of wild oats, a timing slightly later than recommended for post emergent herbicide treatment, gave the best results, reducing seed yield by 97%. An integrated program which best minimises seed bank populations and does not solely rely on herbicides, will be the most successful for the long term control of wild oats in southern Australian farming systems.

Declaration

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being available for loan and photocopying.

Brett Nietschke

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Thats all folks, South America here we come.....

"He has achieved success who has lived well,

laughed often and loved much"

(Bessie Anderson Stanley)

Chapter 1

1. General introduction

In a review of the principal weeds of major crops throughout the world, Holm *et al.* (1991) declares "it would be difficult to find a more serious group of weeds in cereals than the collection of plants universally referred to as 'wild oats'." Wild oats are responsible for reductions in crop yield, grade and quality reduction, cleaning costs, costly chemical and cultural control measures, and are hosts for various root diseases and pathogens of cereals. On a global basis, Jutsum and Bryan (1992) estimate over 10% of all herbicide inputs are aimed at controlling wild oats - an astounding outlay for a specific weed species. In Australia, two wild oat species predominate in cropping regions, *Avena fatua* L. and *A. ludoviciana* Durieu (Thurston and Phillipson, 1976), causing estimated annual losses of $100m (Medd, 1997). These species probably rank as the most widespread and important weeds of Australian cropping systems (Medd, 1996b).

Southern Australia is characterised by a winter dominant rainfall distribution and a summer drought that commonly lasts for five months. Thus for broadacre farming the choice of crops is restricted to winter growing annuals. In the past, farmers traditionally practiced a ley farming system with rotations based on pasture/wheat (*Triticum aestivum*) or pasture/wheat/fallow, that integrated sheep (*Ovis aries*) and or cattle (*Bos taurus*) to graze the annual legume based (*Trifolium* and *Medicago* spp.) pastures. The legume pasture phase provided high quality feed for livestock, extra soil nitrogen for the following crop and an opportunity to manage troublesome cropping weeds such as wild oats. Strategies such as livestock grazing, hay cutting and pasture topping (both mechanical and later chemical) were utilised to prevent weed seed production and significantly deplete the seed bank before entering the crop phase. In addition, multiple pre-sowing tillage operations, delayed crop sowing and the burning of crop residues were weed management options generally utilised in the crop phase.

The ley farming system in southern Australia was practised almost without interruption until the 1970's. However, the advent of selective herbicides in the late

1970's (Acetyl Coenzyme A Carboxylase (ACCase) inhibitors) and early 1980's (acetolactate synthase (ALS) inhibitors), gave opportunities for farmers to crop more intensively by controlling weeds in-crop. Furthermore, the promotion of conservation farming practices such as reduced tillage and increased stubble retention, and a heavy emphasis on early seeding of crops to maximise yields, necessitated the increased use of in-crop selective herbicides. Apart from weed control efficacy, these practices proved beneficial for soil structure, soil fertility and in controlling root diseases of cereals.

By 1982 the persistent use of selective herbicides in southern Australia (particularly the ACCase inhibitors), resulted in the development of herbicide resistance in *Lolium rigidum* Gaudin (annual ryegrass). By the end of the decade, resistance had also been confirmed in two other major weeds of southern Australia, *A. fatua* and *A. ludoviciana*. The 1990's saw a relative decline in the value of livestock production and more favourable economic returns from grain enterprises. This resulted in many farmers pursing prolonged periods of continuous cropping. This system relied heavily on in-crop selective herbicides for weed control and subsequently the incidence of herbicide resistance increased dramatically. Such is the magnitude of the problem, thousands of farms across southern Australia are now affected (mainly with resistant *L. rigidum* populations), with a further 14 weed species also having developed resistance to herbicides (J. Matthews pers. comm.).

The widespread development of herbicide resistance has emphasised the vulnerability of selective herbicides as a sustainable weed control option. Additionally, farmers are likely to be forced to reduce herbicide use for both economic and environmental reasons. It is now widely held that integrated weed management (IWM) - the planned and managed use of cultural, chemical and biological measures, is essential for sustainable weed control in southern Australian farming systems. Whilst many of the principles of IWM are already understood, the economic need for farmers to pursue prolonged periods of cropping means that implementation of these principles is more difficult. Here-in lies the challenge - to manage recalcitrant weeds such as wild oats that are developing or have developed resistance to herbicides, but continue cropping intensively.

A range of IWM techniques can be used to minimise herbicide resistant wild oat populations in southern Australian farming systems, however, a successful management program must prevent wild oat seed return to the soil (Thill *et al.*, 1994). Hence, any economically and environmentally acceptable practice that reduces weed establishment, competitiveness, seed production, seed shed or migration is appropriate (Morrison and Bourgeois, 1995). The development of IWM systems must also be supported by a thorough understanding of the population dynamics operating within weed seed banks. However, information on the population dynamics of wild oats in farming systems is currently lacking for southern Australia.

Throughout Australian cropping areas the relative incidence of *A. fatua* and *A. ludoviciana* differ. Both species have traditionally been treated as one, ie. 'wild oats', and little attention has been paid to any biological differences between the two. Specific management practices or environmental conditions may cause each species to behave differently allowing one species to predominate when present as a mixed infestation. In South Australia, *A. fatua* is thought to dominate, but no previous study has been undertaken on the occurrence and distribution of *A. fatua* and *A. ludoviciana*. This has been quantified for a major cropping region of southern Australia, along with the level of herbicide resistance in wild oats for the area.

The focus of this thesis was to determine appropriate strategies for managing wild oats through greater understanding of their ecology and biology. Population dynamics studies were undertaken to define the seed bank decline and emergence pattern of herbicide susceptible and resistant wild oat biotypes. This information will be central to the development of successful long term management strategies for wild oats in southern Australian farming systems. The management techniques evaluated include; the burning of residues from cereal crops and flamprop-*m*-methyl as a late applied post emergent herbicide treatment.

Chapter 2

2. Literature Review

2.1 Introduction

Wild oats are among the most widespread and economically damaging weed species of temperate crops throughout the world (Holm *et al.*, 1991). They are annual grasses, predominantly self pollinating, and have substantial genetic diversity which allows them to exploit a wide range of niches across different geographical areas (Imam and Allard, 1965; Whalley and Burfitt, 1972; Van Der Puy, 1986).

Despite the volume of research undertaken on the biology and population dynamics of wild oats and the range of management techniques, including herbicides, utilised for their control, wild oats possess successful survival mechanisms enabling them to flourish in agricultural or disturbed habitats (Purvis and Jessop, 1985). These include; early seed shedding ability, variable seed dormancy mechanisms, extended germination habit and a strong competitive ability. In addition, wild oat populations have developed resistance to herbicides, further ensuring persistence of the species in farming systems.

The following review examines literature pertaining to wild oats in broadacre farming systems. The review aims to develop a thorough understanding of the biology and ecology of wild oats so control measures can be improved through exploiting any weakness in its life cycle. The development and incidence of herbicide resistance in wild oats world-wide, and the ramifications resistance has for management in southern Australian farming systems are discussed.

2.2 Biology and ecology of *Avena* spp.

2.2.1 Genus *Avena*

The genus *Avena* comprises cultivated oats (eg. *A. sativa* and some varieties of *A. strigosa* Schreb.), truly wild plants (ie. normal constituents of local vegetation in areas where they are native, eg. *A. hirtula* (Lag.) Malzew and *A. wiestii*) and weeds

(Thomas and Jones, 1976). Of the weedy types, there are many species and numerous subspecies (Baum, 1977).

A. fatua L. and *A. sterilis* L. are the two most important *Avena* weeds of cereal and arable crops throughout the world. *A. sterilis* shows considerable variation with the species being divided into three subspecies. These include ssp. *ludoviciana* Malzew which is often called *A. ludoviciana* Durieu, ssp. *maxima* Perez Lara. and spp. *macrocarpa* Moench (Thomas and Jones, 1976). Both *A. fatua* and *A. sterilis* thrive under conditions similar to cultivated oats and can hybridise easily with *A. sativa* (Vavilov *et al.*, 1992). The weedy types are unsuitable as grain crops because their seeds fall as they ripen and their seed dormancy ensures they germinate over several years (Thurston, 1982).

Considerable physiological and morphological variation has also been reported in weedy *Avena* spp. (Thurston, 1957; Whalley and Burfitt, 1972; Miller *et al.*, 1982; Efthimiadis *et al.*, 1993). For the purpose of this thesis the following terms are defined.

Strain: A species phenotype which is classified according to a specific character such as seed colour or seed hairiness.

Biotype: Members of a species which have developed into a sub-population due to a specific influence. A biotype has a similar genetic constitution eg. resistance to herbicides.

Here-in after, weedy *Avena* spp. will be referred to as '*Avena* spp.' For simplicity, the terms '*Avena* spp.', 'wild oats' and 'wild oat' are used interchangeably and refer to '*A. fatua*' and or '*A. ludoviciana*' throughout the thesis.

2.2.2 Origin and spread

Wild oats have been weeds of agriculture for at least 4000 years (Malzew, 1930), dating back to the Greek and Roman empires (Van Der Puy, 1986). Malzew (1930) claims the centre of origin of *A. fatua* is probably South West Asia, with *A. sterilis*, including *A. ludoviciana*, originating from Asia Minor. In recent times, these species have spread to most arable regions of the world, including Australia. According to Whalley and Burfitt (1972) it is not precisely known when wild oats were first

introduced to Australia, nor how many different introductions occurred. However, Paterson (1976a) suggests wild oats were originally introduced to Tasmania from the United Kingdom (UK) as a cereal grain contaminant. By the 1830's the weed had entered Western Australia through settlement (Paterson, 1976a) and in 1895 was recorded as a "terrible pest to the farmer" in New South Wales (Maiden, 1895).

2.2.3 Distribution

A. fatua, by far the most widely distributed of the wild oat species, is a weed of more than 20 crops in 55 countries (Holm *et al.*, 1991). It occurs throughout north west Europe, Asia, North America, and various other cereal growing areas of the world (Coffman, 1961; Thurston and Phillipson, 1976). Conversely, *A. sterilis* generally occurs in Mediterranean climatic regions of the world. Of the subspecies of *A. sterilis*, *A. ludoviciana* is the most widespread and abundant (Thurston and Phillipson, 1976). The third most important weedy *Avena* species in the world is *A. barbata* Pott. (Holm *et al.*, 1991). Like *A. sterilis* it is a Mediterranean species (Thurston and Phillipson, 1976), but in Australia is rarely seen in crops due to its low seed dormancy and consequent early germination habit (McNamara, 1972). *A. barbata* is largely restricted to roadsides, undisturbed land and pasture (Whalley and Burfitt, 1972; Paterson, 1976a).

In Australia, *A. fatua* and *A. ludoviciana* are the species which predominate cropping regions (Thurston and Phillipson, 1976). Most occurrences of wild oats involve mixed infestations of these species, particularly in southern New South Wales, Victoria and South Australia (Mansooji *et al.*, 1992; Medd and Jones, 1996). Nevertheless, the relative incidence of each species differs throughout the country. In Western Australia and southern New South Wales *A. fatua* predominate, whilst *A. ludoviciana* occurs more frequently in northern New South Wales and southern Queensland (McNamara, 1966; Whalley and Burfitt, 1972; Cartledge, 1973; Paterson, 1976a; Wilson, 1986). In South Australia, Heap and Stephenson (1986) suggested *A. fatua* to be more prevalent than *A. ludoviciana*, but gave no supporting evidence detailing the relative abundance of each species.

2.2.4 Identification

Avena species are best separated by their spikelet characteristics at maturity (Table 2.1). They cannot be identified during the vegetative growth phase.

Table 2.1 Diagnostic features of the two main wild oat species that infest Australian cropping regions (from Thomas and Jones, 1976).

Character	*A. fatua*	*A. ludoviciana*
Awn on third seed	Present	Absent
Abscission scar	Present at base of every seed	Present at base of the primary seed only (secondary and tertiary seeds end in a stalk)
Shedding of mature seed	Seeds of spikelet fall separately	Seeds of spikelet fall together as a unit. Force is necessary to separate the grains within a spikelet

2.2.5 Seed shedding and dispersal

Due to the presence of abscission zones at the base of each wild oat seed (*A. fatua*) or whole spikelet (*A. ludoviciana*), seeds naturally shed at maturity (Dadd, 1957) with their awns behaving like a self-burial mechanism (Cussans, 1976). *Avena* spp. do not naturally disperse over long distances as most seeds fall within 2 m of the parent plant, however, they are extensively spread through human activity (Thurston and Phillipson, 1976). In mixed farming systems, the spread of wild oats can be attributed to transportation in fodder (Thomas *et al.*, 1984), straw (Wilson, 1970), use of contaminated grain (Elliott and Attwood, 1970), or dispersal by agricultural machinery (Thurston and Phillipson, 1976).

2.2.6 Seed production

Avena spp. usually have two or three seeds per spikelet, however, total seed production is dependent on competition and many other factors. These may include; plant density, crop density, time of emergence (Medd, 1996a) and soil moisture (Peters, 1982). Understandably, the amount of seed produced per plant (fecundity) is highly plastic. An individual wild oat plant growing without competition can produce at least 6750 seeds (Thurston, 1982), but generally yield 40 to 50 seeds growing with strong competition in a cereal crop (Cussans, 1976).

Early emerging wild oat plants (relative to the crop) tend to be the most competitive and produce the most seed. Peters and Wilson (1983) found that *A. fatua* plants emerging before a spring barley (*Hordeum vulgare*) crop, yielded five times as many seeds per plant as those emerging between the crop two and three leaf stages. The seed produced from early emerging plants also tends to germinate faster, produce more vigorous plants and are naturally shed before harvest, thus perpetuating the wild oat problem (in future years) (Zimdahl, 1990).

2.2.7 Seed dormancy

Seed dormancy is a genetically controlled lack of synchronism in the development and functioning of the structural and biochemical components of the seed (Simpson, 1992). In simple terms, a viable seed is dormant if it does not germinate under conditions favourable for seedling growth and development (Egley and Smith, 1983).

Three types of seed dormancy exist; innate, induced and enforced (Roberts, 1972; Harper, 1990). Innate dormancy (also known as primary, natural, inherent or endogenous dormancy) is present immediately at the time of dispersal from the parent plant. Such dormancy prevents the seed from germinating on the plant and usually for some time after the ripe seed is shed or harvested. After a seed has lost its innate dormancy and if unable to germinate under suitable conditions, it can move into induced (or secondary) dormancy. Enforced dormancy describes the condition where viable seeds do not germinate because of some environmental restraint, such as shortage of water or low temperature (Roberts, 1972; Egley and Smith, 1983; Harper, 1990).

Factors influencing the state of dormancy in wild oat seeds are not consistent across studies. Dormancy develops as wild oat seeds mature, however, conditions during ripening affect the speed of onset of viability and dormancy (Thurston, 1963). Thurston (1959) found that dormancy in *A. fatua* and *A. ludoviciana* seeds lasts for at least two months following seed maturity, while, in contrast, Quail and Carter (1969) determined that primary seeds of *A. ludoviciana* germinated a week after maturation. According to Cousens and Mortimer (1995), *A. ludoviciana* seeds usually have less innate dormancy than *A. fatua* seeds.

Avena spp. contain various complex dormancy mechanisms. According to Simpson (1992), light, temperature, gaseous composition, inorganic and organic substances and particularly water status may act individually or interact, to induce, sustain and terminate seed dormancy in different ways according to genotype and age. Subsequently the proportion of dormant wild oat seeds differs between species, strains and locality (Quail and Carter, 1969; Peters, 1991).

Wild oat seeds from a single plant vary in their dormancy level. This is dependent on panicle size, panicle position and spikelet position (Thurston, 1963; Chancellor, 1976). Several authors (Quail and Carter, 1968; Peters, 1986) have determined that secondary seeds have a greater longevity (longer dormancy) than primary seeds. Quail and Carter (1968) suggest the function of primary seeds is to provide a dense infestation the year after seeds have shed, whilst the secondary seeds ensure species survival.

Seed dormancy can also be influenced by agronomic management (Naylor and Jana, 1976), including; crop rotation (Marzolo and Speranza, 1993), summer fallowing (Jana and Thai, 1987), nitrogen fertilisers (Sexsmith and Pittman, 1963; Agenbag and De Villiers, 1989) and crop type (Richardson, 1979).

Seed dormancy is a key process controlling wild oat recruitment (germination) (Medd, 1996a). However, due to the complexity of dormancy, forecasting wild oat emergence from the seed bank is difficult (Wilson and Peters, 1992). In addition, seed recruitment is influenced by the environment (Morrison and Friesen, 1996). Little work has been undertaken to understand recruitment or predict recruitment behaviour, however, annual rates of recruitment of up to 60% of the seed bank have been noted (Medd, 1996a).

2.2.8 Emergence pattern

Despite seed dormancy, the majority of wild oat seeds germinate in the year after production, with the remaining seed doing so over several seasons. However, *Avena* spp. show complex patterns of variation in germination, both between and within populations (Marshall and Jain, 1970). The pattern of germination can fluctuate widely with seasons (Medd, 1996a) as can the density of infestations. Both genetic

and environmental factors contribute to this variable emergence behaviour (Naylor and Jana, 1976; Jana and Naylor, 1980).

Avena spp. demonstrate an extended germination pattern. In southern Australia, emergence usually occurs as an initial wave soon after the onset of winter rainfall ('break of the season') and is followed by smaller periodic emergence events until early spring. Seed dormancy is the key factor controlling the dynamics of this process (Medd, 1996a). Harper (1990) suggests *Avena* species are delayed in their germination as the attached lemma and palea hinders the entry of water into the seed.

2.2.8.1 Emergence of *A. fatua* and *A. ludoviciana*

A. fatua and *A. ludoviciana* can produce similar emergence patterns (Aibar *et al.*, 1991), however, the two species generally differ in their pattern of emergence (Thurston, 1951; Thurston, 1961; Quail and Carter, 1968). This difference seems more pronounced in the northern hemisphere than Australia. In the UK, *A. fatua* is referred to as the common or spring wild oat and *A. ludoviciana* the winter wild oat. These common names relate to the periods of peak germination of the two species in the northern hemisphere (McNamara, 1966). In Australia, a greater percentage of *A. fatua* has been reported to emerge in autumn, whereas most *A. ludoviciana* appear in winter (Quail and Carter, 1968).

Once the dormancy of *Avena* spp. seed is relieved, soil moisture and soil temperature are the two major factors which trigger germination. Researchers throughout the world (Quail and Carter, 1968; Whittington *et al.*, 1970; Fernandez-Quintanilla *et al.*, 1990) have determined that the optimum temperature requirement for germination is lower for *A. ludoviciana* than *A. fatua*. In northern Australia, Quail and Carter (1968) reported that a higher proportion of *A. ludoviciana* germinates and emerges than *A. fatua* below 10°C, but the opposite occurs above 20°C. This characteristic probably explains the early season emergence of *A. fatua* and the winter emergence of *A. ludoviciana* noted by Quail and Carter (1968). Germination was inhibited in summer due to high temperatures coupled with insufficient moisture (Quail and Carter, 1968).

2.2.9 Seed bank longevity

The seed bank (reserves of viable weed seeds present in the soil and on its surface) longevity of *Avena* spp. has been the subject of much speculation. Farmers often report that wild oats can survive in the soil for many years, even up to 75 years, but experimental evidence does not confirm this (Holm *et al.*, 1991). This exaggeration of wild oat persistence is attributed to the input of new seed from survivors, not seed dormancy or long term viability mechanisms as commonly thought (Wilson, 1978; Medd *et al.*, 1995). However, there is a small, long lived portion of the seed bank which is intractable, especially in undisturbed soil, making it virtually impossible for total eradication (Wilson and Peters, 1992; Medd, 1996a). In cropping systems, wild oat populations decline rapidly when seed production is prevented (Medd *et al.*, 1995; Medd, 1996a). For example, in northern New South Wales, Martin and Felton (1993) reported the seed bank half-life of a population comprising both *A. fatua* and *A. ludoviciana* was six months. Soil type does not greatly affect the duration of *Avena* spp. seed survival, although peaty soils appear to encourage germination (Chancellor, 1976).

Previous work (Thurston, 1961) comparing the seed bank life of *A. fatua* and *A. ludoviciana* indicated that *A. ludoviciana* has a shorter seed longevity than *A. fatua.* Conversely, Sanchez del Arco *et al.* (1995) concluded no firm evidence has been collected in this regard. However, Navarrete and Fernandez-Quintanilla (1996) compared data on the seed bank decline of both species and suggested that *A. ludoviciana* is less persistent.

2.2.9.1 Crop versus pasture

The persistence of *Avena* spp. seeds buried in the soil may depend on the seed source, environmental conditions of the site and cultural practices used (Sanchez del Arco *et al.*, 1995). A review of literature by Chancellor (1976) concluded that the length of wild oat seed survival in arable land is between two and nine years, with four to five years being the average. Since Chancellor's review, subsequent research has confirmed that the seed bank life of wild oats in cropping systems is relatively short (Wilson, 1978; Martin and Felton, 1993; Sanchez del Arco *et al.*, 1995).

Under pasture or grass land, Chancellor (1976) concluded that the maximum seed longevity of wild oats is similar to that in arable land. However, Thurston (1966) and Wilson and Phipps (1985) in the UK found that pasture seed banks are not depleted to the same extent as for arable situations, due to the lack of soil disturbance. The seed bank decline of wild oats under pasture conditions in Australia is unknown, apart from work by Mansooji (1993) who noted that the seed bank of an *A. ludoviciana* population was reduced by 97% in 3.5 years.

2.2.9.2 Depth of seed burial

Deeper burial of wild oat seeds reduces seedling emergence and plant establishment. In a naturally occurring population of *A. fatua*, Holroyd (1964) determined that while emergence occurred up to a soil depth of 19 cm, 70% of seedlings arose from the top 7.5 cm. According to Chancellor (1976), the effect of depth of seed burial on *Avena* spp. seed longevity is inconsistent. Zorner *et al.* (1984) working with *A. fatua*, Sanchez del Arco *et al.* (1995) with *A. ludoviciana*, and Quail and Carter (1968) with both species, found that depth of burial had little influence on seed survival. Conversely, other studies recognise seed persistence is greater at depth, particularly below five cm (Chepil, 1946; Thurston, 1961; Banting, 1966; Miller and Nalewaja, 1990).

2.2.10 Seed bank decline

Loss from seed banks is through seed germination, death through metabolic failure, predation, or removal from the soil. The sum of these fates gives a seed bank decline curve (Medd, 1987). The decline pattern of wild oat seeds in arable soils (Martin and Felton, 1993) and under pasture (Forbes, 1963; Thurston, 1966) approximates to an exponential decrease; ie., a constant percentage is lost each year. Sanchez del Arco *et al.* (1995) reported seed bank decline followed an exponential pattern only on an annual basis, with the greatest loss occurring in the first year. Annual rates of seed decline in cropping systems generally range from 60 to 80% (Wilson, 1978; Barralis *et al.*, 1988; Medd, 1990; Medd, 1996a).

2.3 Agricultural importance of *Avena* spp.

2.3.1 Status as a weed

The widespread distribution of *Avena* spp. and its impact on modern agriculture practice make wild oats one of the worlds most successful weeds of cropping systems (Combellack, 1992). *Avena* spp. are responsible for reductions in crop yield, grade and quality dockages, cleaning costs, costly chemical and cultural control measures, and are hosts for various root diseases and pathogens of cereals (Sharma and Vanden Born, 1978; Medd, 1996b).

Wild oats are strongly competitive with a wide range of mostly temperate crops, but are principally noted as a problem of cereals (Sharma and Vanden Born, 1978; Elliott *et al.*, 1979; Holm *et al.*, 1991; Combellack, 1992). In Australia, *Avena* spp. are the most prevalent grass weed of cereals in New South Wales (Leys and Dellow, 1986; Martin *et al.*, 1988; Lemerle *et al.*, 1996) and Queensland (Wilson, 1986). In South Australia, farmers ranked wild oats second behind *L. rigidum* as the most important grass weed of broadacre farming systems (Mayfield and Edwards, 1992).

2.3.2 Competitive ability

Competitiveness with crops is the main negative aspect of *Avena* spp. (Combellack, 1992). The ability of wild oats to reduce crop yields has been attributed to an extensive root system (Pavlychenko and Harrington, 1934), high net assimilation rate during early growth stages (Pavlychenko and Harrington, 1934; Thurston, 1959) and its height and leaf area distribution which reduce light penetration to the crop canopy (Cudney *et al.*, 1991).

Avena spp. cause considerable crop yield reduction. However, the extent to which wild oats affect crop yield depends on weed and crop density, time of emergence of the weed and crop, soil type, environmental influences (Chancellor and Peters, 1976) and numerous agronomic factors (see 2.4.1.3). In the UK, Wilson *et al.* (1990) concluded that low densities of *A. fatua* are likely to result in cereal yield losses of 1% for each *A. fatua* plant/m^2. Conversely, in Western Australia a density of 50 *A. fatua* plants/m^2 reduced wheat yields by about 20% (G. Gill, pers. comm.). *Avena* spp. are noted for their reduction of cereal, pulse and oilseed yields in southern Australian farming systems. They are the most competitive annual grass of wheat in

southern Australia (Poole and Gill, 1987). Reductions in wheat yields of up to 44 to 78% have been reported (Reeves *et al.*, 1973; Philpotts, 1975; McNamara, 1976; Radford *et al.*, 1980; Martin *et al.*, 1987).

Reports from overseas (Sharma and Vanden Born, 1978) suggest that crop losses due to competition may also affect crop quality. Bell and Nalewaja (1968b) and Chow and Dorrell (1979) determined that wild oats severely affect flax seed quality and oil content. Chow and Dorrell (1979) also demonstrated that wild oats reduce canola oil quality. Conversely, cereal grain quality (protein level and kernel size) was reported to be rarely affected (Bell and Nalewaja, 1968a; Chancellor and Peters, 1976). In Australia, there are no documented studies of the effect of wild oats on grain quality.

2.3.3 Grain contamination

The majority of wild oat seeds are shed before crop harvest allowing the reinfestation of fields, whilst the later ripening seeds remain as impurities in the grain sample (Bowden, 1971; Sharma and Vanden Born, 1978). Cousens *et al.* (1985) found that the percentage of harvested grain contaminated with *A. fatua* increases as its density in the crop increases. In addition, the level of contamination can be seasonal and price dependent as market forces determine the extent of weed control and post-harvest grain cleaning (Medd, 1996b). If seed grain is contaminated, crops can easily be reinfested with wild oats. In the UK, Elliott and Attwood (1970) found that 15% of cereal seed drills were contaminated with *Avena* spp. at sowing.

Avena spp. have been recorded as a consistent grain contaminant of storage terminals throughout Australia (McNamara, 1966; Marshall, 1986; Medd and Pandey, 1990). The downgrading of heavily contaminated grain may result in the loss of premium payments for wheat, which would otherwise have been classified above general purpose or feed grain quality (Wilson, 1979a; Medd, 1996b).

2.3.4 Host for diseases

Annual grasses of southern Australia (*Avena* spp., *L. rigidum*, *Bromus* spp., *Vulpia* spp.) are important not only because they compete with crops, but as alternative hosts to various root diseases of cereals, including *Heterodera avenae* and *Gaeumannomyces graminis*. Such grasses, particularly as a component of pastures,

are a source of infection from which the diseases infect crops and cause serious yield loss (Code, 1986). Meagher (1972) determined that *A. fatua* is a major host of *H. avenae*, causing a greater multiplication of cysts than *L. rigidum*.

Avena spp. also act as an important refugia for pathogens that attack cultivated oats (eg. *Puccinia coronata*, *P. graminis avenae,* barley yellow dwarf virus) (Burdon and Marshall, 1992). Plants that survive throughout summer and the following autumn carry inoculum over from one winter crop season to the next. Furthermore, the explosion in wild oat numbers that occurs in response to the first widespread autumn rains produces a flush of potentially susceptible host material well in advance of a later sown cultivated oat crop. These plants provide a host for the early increase of *P. coronata* and *P. graminis avenae* and a 'springboard' for the development of rust epidemics on newly planted crops (Burdon and Marshall, 1992).

2.3.5 Allelopathy

Many crop and weed species can cause an inhibitory effect on the germination and growth of other plant species through the production of allelochemicals. This is known as allelopathy (Rice, 1974). *A. sativa* can produce allelochemicals and inhibit the growth of wheat seedlings (Guenzi and McCalla, 1966). Similarly, wild oats have the ability to be allelopathic to other plants (Tinnin and Muller, 1971; Tinnin and Muller, 1972), including wheat. Schumacher *et al.* (1983) and Pérez and Ormeño-Nuñez (1991) found that root exudates from *A. fatua* inhibited root, coleoptile and leaf growth of spring wheat, and thus implicated allelopathy in the reduction of crop yields. However, separation of the influence of wild oat competition from allelopathy on spring wheat growth in the field is difficult (Schumacher *et al.*, 1983).

2.3.6 Economic losses

Avena spp. are both difficult and expensive to control in crops (Wilson, 1979a). Sharma (1979) estimates wild oats cause annual losses of US$500m in Canada and the USA. In 1987, Medd and Pandey (1990) calculated an annual loss of $42m to the Australian wheat industry from crop yield losses, herbicide and associated application costs for wild oat control. The current loss is probably about $100m (Medd, 1997). On a global basis, Jutsum and Bryan (1992) estimate over 10% of all herbicide inputs ($1240m) are aimed at controlling wild oats.

The continual use of selective herbicides has resulted in the development of herbicide resistant wild oat populations in various countries throughout the world (see 2.5.5). Herbicide resistance generally necessitates more expensive control options or additional control inputs, causes greater potential losses and, possibly opportunity costs through having to divert to less profitable enterprise options (Medd, 1996b).

2.4 Control of *Avena* spp.

A range of techniques have been utilised in broadacre farming systems for the control of *Avena* spp. Initially farmers relied on cultural (non-chemical) control methods for wild oat management, but since the 1960's selective herbicides have become the preferred method of control (Combellack, 1992). However, the development of herbicide resistance has again necessitated the use of a range of control techniques in an integrated manner for the sustainable control of wild oats. World-wide control options relevant to managing *Avena* spp. in southern Australian farming systems are reviewed in this section.

2.4.1 Cultural control

The cultural weed strategies that can be utilised in farming systems are many and varied. A high level of control of *Avena* spp. can be achieved with cultural methods, although efficacy varies with climatic conditions and may change between regions and years (Hunter, 1983). Cussans and Wilson (1976) argue cultural techniques are generally more appropriate for the containment of low wild oat infestations, than for the reduction of high populations.

2.4.1.1 Cultivation

The effects of tillage on the population dynamics of *Avena* spp. are complex and varied (Navarrete and Fernandez-Quintanilla, 1996), however, various trends are evident in the literature. Cultivation is known to encourage wild oat germination (provided it is conducted during the period of the year when germination occurs (Chancellor, 1976)), and is therefore a key factor controlling the persistence of wild oats (Simpson, 1992).

Both the timing and type of cultivation influence wild oat populations, as the burial of wild oat seed can favour the maintenance of dormancy, thus prolonging longevity. If seeds are brought to the surface by subsequent tillage, they are released from dormancy and become available for recruitment. Consequently, wild oat populations may increase more under pre-sowing cultivations than for practices which involve no or minimal soil disturbance during seedbed preparation, such as direct drilling (Medd, 1990; Walsh, 1995). Delaying cultivation until several months after harvest allows considerable natural mortality of seeds before burial (Wilson, 1972; Wilson and Cussans, 1975). While, Wilson (1978) and Wilson and Phipps (1985) found that wild oat seed banks decline more rapidly using tyned implements compared with deep ploughing.

2.4.1.2 Delayed seeding

Delaying the date of seeding allows control of emerged seedlings, thus reducing wild oat infestation levels in the subsequent crop. This was successfully demonstrated by Whybrew (1964) in the UK. Conversely, Walsh (1995) in southern Australia determined that delayed seeding of wheat did not affect wild oat populations, due to the extended germination pattern of the weed. Furthermore, under most Australian conditions, delayed seeding inflicts a grain yield and/or quality penalty and is therefore considered an uneconomic general control method. Although delayed seeding is not recommended, Thill *et al.* (1994) suggests a sensible compromise is to plant fields with the worst wild oat populations last, so as to minimise the level of infestation in the competing crop. This practice is widely used in Australian agriculture as farmers consciously plant their most weed infested fields late in the seeding program.

2.4.1.3 Crop competition

Competitive interactions between *Avena* spp. and crops are a complex issue. Several agronomic factors will influence the extent to which crop yield is reduced by wild oats, and the amount of wild oat seed returned to the soil (Thill *et al.*, 1994). Crops (O'Donovan *et al.*, 1983) and crop cultivars (Balyan *et al.*, 1991; Ramesh Kumar and Katyal, 1993; Lanning *et al.*, 1997) differ in competitive ability with wild oats. Similar situations have been described by Lemerle *et al.* (1995) with *L. rigidum* in

southern Australia. Increasing the seeding rates of cereal crops generally reduces *Avena* spp. competition and seed production (Radford *et al.*, 1980; O'Donovan *et al.*, 1983), whilst shallow planting of quality seed gives the crop maximum competitive advantage in the early stages of growth (Cussans and Wilson, 1976). Crops sown in narrow row spacings are equal to, or, more competitive with wild oats than widely spaced crop plants (Thill *et al.*, 1994).

2.4.1.4 Fertiliser use and placement

Conflicting views exist on the relative competitiveness of root systems of *Avena* spp. and cereal crops (Pavlychenko, 1937; Martin and Field, 1987; Satorre and Snaydon, 1992; Bingham, 1995). This may explain the variable yield responses to fertilisers (particularly nitrogenous fertilisers) in interference studies between *Avena* spp. and cereals (Cousens and Mortimer, 1995). In southern Australia, Walsh (1995) found the application of fertiliser (nitrogen and phosphorus) failed to achieve any reduction in weed growth and development, indicating no competitive advantage to either the crop or weed. Watkins (1971) demonstrated that nitrogen fertiliser can stimulate *Avena* spp. emergence before sowing, but has little affect as a long term means of reducing wild oat infestations. Banding nitrogen fertiliser near the crop seed appears to favour the crop, and is thus preferable to broadcasting fertiliser which favours wild oat growth (Thill *et al.*, 1994).

2.4.1.5 Windrowing and weed seed collection at harvest

Windrowing crops prior to the shedding of wild oat seeds may lead to greater seed retention and capture at harvest. However, as captured seed is usually carried with the cereal grain, the cost of re-cleaning wild oat contaminated grain must be evaluated against the potential benefits (Matthews, 1994).

Evidence from overseas suggests that wild oat seed capture is achievable with chaff collectors (Thill *et al.*, 1994). In the UK, Wilson (1970) was able to catch 84% (in the grain bin) of the total seed produced in an early maturing winter barley crop. These results do not seem applicable to Australian conditions, as the vast majority of wild oat plants shed their seed before or during grain harvest, and only a small proportion of seed can be caught (either in a separate collection unit or grain bin).

However, it does suggest harvest time, environment and even wild oat species/biotypes may influence seed catching efficacy.

2.4.1.6 Crop residue burning

Wild oat seed can be destroyed on the soil surface by burning the residues (stubble) of crops. Seed kill is maximised when burning is conducted directly after harvest (Molberg and Banting, 1973; Wilson and Cussans, 1975). Additionally, burning can stimulate surface seed emergence by modifying seed dormancy of the survivors (Viel, 1963; Whybrew, 1964; Wilson and Cussans, 1975). Whybrew (1964) and Wilson and Cussans (1975) in the UK concluded that stubble burning by itself will not prevent population growth. This is most likely the case for Australian agriculture and, in any event, the practice is generally discouraged because of the recognised benefits of stubble retention.

2.4.1.7 Crop rotation

Wild oat infested crops, cut for hay or silage before seed shed, can greatly reduce seed rain (Cussans and Wilson, 1976; Thill *et al.*, 1994). In the UK, continuous spring barley cut for silage reduced wild oat emergence to nil after three years (Wilson and Phipps, 1985). The green manuring (plough down) of crops should be an equally effective control method if wild oat seed production is prevented. Diverting land use to a pasture phase also provides the opportunity to reduce seed production, either by strategic grazing, mechanical slashing or herbicide use (Jenkinson, 1976; Bentley, 1990).

In northern Australia, continuous winter cereals did not reduce wild oat populations and most likely neither do winter cereal-chickpea (*Cicer arietinum*) rotations, due to the poor competitive ability of chickpeas (Medd, 1997). However, Philpotts (1975), Wilson *et al.* (1977) and Martin and Felton (1993) effectively reduced wild oat seed reserves through clean winter fallowing in association with a rotation from wheat to sorghum (*Sorghum bicolor*). Fernandez-Quintanilla *et al.* (1984) similarly demonstrated the value of summer break crops and winter fallowing in a Mediterranean climate.

2.4.2 Chemical control

In the late 1950's, diallate and barban were the first selective avenacides (wild oat herbicides) introduced to Australian cropping systems. They selectively controlled *Avena* spp. in cereal crops (Hutson and Roberts, 1987; Medd, 1992). Today, a range of selective herbicides are utilised for the control of wild oats in Australian cereal and broadleaf crops (Table 2.2). Additionally, non-selective herbicides (paraquat, diquat and glyphosate) are used as a 'knockdown' prior to sowing or for spray-topping to control weed seed production (discussed below).

The sequence of events leading to the death or injury of susceptible plants following herbicide application is defined as herbicide mode of action (Kirkwood, 1983). Herbicides are classified according to their mode and site of action, and chemical structure. Different herbicide classes exist within herbicide groups, and for this thesis the following terms are used within the defined context.

Herbicide group: Herbicides classified according to their site of action.

Herbicide class: A sub-group of herbicides within a herbicide group, classified according to their chemical structure.

Table 2.2 Selective herbicides for control and suppression of *Avena* spp. in Australia (adapted from Chambers, 1995).

Herbicide group	Active constituent
A (APP's)	Clodinafop-propargyl, Diclofop-methyl, Fenoxaprop-*p*-ethyl, Fluazifop-*p*, Haloxyfop, Propaquizafop, Quizalofop-*p*-ethyl
A (CHD's)	Clethodim, Sethoxydim, Tralkoxydim
B	Imazethapyr
C	Atrazine, Diuron, Metribuzin, Simazine
D	Pendimethalin, Trifluralin
E	Triallate
F	Amitrole
K	Flamprop-methyl, Flamprop-*m*-methyl

2.4.2.1 Selective herbicides

Herbicides from the aryloxyphenoxypropanoates (APP's) and cyclohexanediones (CHD's) classes are toxic to most grass species, whereas nearly all dicot species remain unaffected. They are widely used in field crops as they target *L. rigidum*, which regularly co-exists with *Avena* spp. throughout southern Australia. APP's were introduced in the late 1970s and CHD's several years later. Each class contains herbicides that are selective (eg. diclofop-methyl, tralkoxydim) or non-selective (eg. fluazifop-*p*, sethoxydim) in cereal crops. The chemistry of APP's and CHD's differ structurally, but both classes interfere with the key enzyme for fatty acid biosynthesis, Acetyl Coenzyme A Carboxylase (ACCase) (Devine and Shimabukuro, 1994). Hence, they are collectively known as 'ACCase inhibiting herbicides' or 'ACCase inhibitors'.

Avenacides that do not inhibit the ACCase enzyme are collectively termed 'non-ACCase inhibitors'. The most important non-ACCase inhibitors include, triallate (used in cereal and broadleaf crops), simazine (lupins (*Lupinus angustifolius* and *L. albus*) and faba beans (*Faba vulgaris*)), flamprop-methyl and flamprop-*m*-methyl (wheat, triticale (X *Triticosecale*) and safflower (*Carthamus tinctorius*)), imazethapyr (faba beans and field peas (*Pisum sativum*)) and diuron (lupins and field peas) (Chambers, 1995). Furthermore, simazine and atrazine can be utilised for wild oat control in triazine resistant canola (*Brassica napus*). The range of herbicides available, permits flexibility in application timing (pre- or early post emergence), and rotation of both chemical groups and crops.

2.4.2.2 Spray-topping

Avenacides are generally regarded as cost effective tools for conserving crop yield, but in Australia cannot be solely relied upon for population control (Medd, 1992; Medd, 1997). Because of staggered recruitment, late emerging seedlings will escape herbicide treatment, irrespective of whether pre- or early post emergence herbicides are used. Seed produced from these plants, together with those which survive treatment, ensures seed bank levels generally increase. In Australia, this has been reported in herbicide efficacy trials (Patterson, 1977; Wilson, 1979b) and long term experiments where in-crop herbicides were applied annually to control wild oats (Medd, 1990; Martin and Felton, 1993). However, two registered methods, pasture-

topping and crop-topping directly target seed production through the use of non-selective herbicides, in pastures and pulse crops respectively.

In wheat crops, the late application of selective post emergence herbicides applied at the early wild oat tiller elongation stage was found to be a promising strategy to minimise seed production in northern New South Wales (Medd *et al.*, 1992; Medd *et al.*, 1995). Flamprop-methyl and fenoxaprop-*p*-ethyl were the most effective herbicides, reducing seed production by up to 96%. In this experiment actual grain yield was not compared to an early application treatment, however, it is generally recognised that yield is not conserved when application is undertaken at the late timing (Medd, 1997). It has been suggested this method of controlling wild oat seed production be referred to as 'selective spray-topping'. The technique has not been evaluated in southern Australia.

2.5 Herbicide resistance

A wide variety of organisms have developed resistance to pesticides, including arthropods (insects and mites) and pathogens (Georghiou, 1986). Until the late 1980's, resistance had been reported in over 500 species of arthropods and 150 fungal pathogens to insecticides and fungicides respectively (Holt and LeBaron, 1990). The first instance of insecticide resistance was documented in 1914 (Melander, 1914), but resistance was not serious or widespread until potent, highly specific organic compounds such as DDT and organochlorines were introduced in the 1940's. Almost three decades passed before fungicides were widely affected, but when protectants were replaced by more active compounds in the early 1970's, resistance developed within a few years (Green *et al.*, 1990). By the 1980's, resistance of weeds to herbicides had evolved widely.

Resistance is a consequence of basic evolutionary processes. Thus, herbicide resistance in weeds is an example of an evolutionary process in plant species due to environmental changes brought about by man. In response to repeated treatments with highly efficacious herbicides, weed populations change in genetic composition due to the intense selection imposed by herbicides (Maxwell and Mortimer, 1994; Jasieniuk *et al.*, 1996). Like other forms of pest resistance to agrochemicals, herbicide resistance is a world-wide problem and of growing concern.

2.5.1 Definitions

Three types of plant response to herbicides are typically recognised: susceptibility, tolerance and resistance (Holt and LeBaron, 1990). The term 'herbicide resistance' is generally used to describe a characteristic of plant species to withstand substantially higher concentrations of a herbicide than the wild type of the same species (Maxwell and Mortimer, 1994). Various patterns of herbicide resistance have been documented and specific terms are used to describe these patterns in a mechanistic (Hall *et al.*, 1994) and or a practical sense, however, the terms cross and multiple resistance are used interchangeably in the literature (Hall *et al.*, 1994). Individually, these and other terms (listed below) are used within the defined context throughout the thesis.

Susceptible: Susceptibility is the inability of a weed species to withstand a normal recommended herbicide rate.

Tolerance: Tolerance is the innate ability of a weed species to withstand (not be killed) the same rate of herbicide that controls another population of the same or different species. Tolerance has not been selected by the herbicide, instead it is due to the naturally occurring variability within a weed population (LeBaron and Gressel, 1982).

Herbicide resistance: Resistance within a population to only one herbicide. This term is also used in a general descriptive sense.

Cross resistance: Expression of a mechanism that endows the ability to withstand herbicides from different chemical groups (Hall *et al.*, 1994) (resistance to herbicide(s) within classes develop as a result of selection intensity from a different herbicide class). Two broad categories of mechanisms endowing cross resistance, are recognised:

Target site cross resistance: Resistance occurs when a change at the site of action of one herbicide also confers resistance to herbicides from a different herbicide class that inhibit the same site of action.

Non-target site cross resistance: Resistance conferred by a mechanism other than resistant enzyme target sites. Potential mechanisms include reduced herbicide uptake, reduced translocation or enhanced metabolism.

Multiple resistance: Expression (within individuals or populations) of more than one resistance mechanism, endowing the ability to withstand herbicides from different chemical groups (Hall *et al.*, 1994). Resistance to herbicide(s) within the same class develops as a result of selection intensity from herbicide(s) within that class.

2.5.2 Development of herbicide resistance

The evolution of herbicide resistance varies widely between weed populations, since many factors contribute to the rate of appearance of resistance. These include; initial frequency of herbicide resistant individuals, number of individuals treated, mode of inheritance of the gene or genes endowing resistance, and the nature and extent of herbicide use (selection intensity). Additionally, for species in which seed remains residual in the soil seed bank (eg. *Avena* spp.), the rate of appearance of resistance will be slowed by the continued recruitment of susceptible individuals from the soil seed bank (Powles *et al.*, 1997). If resistance incurs a metabolic cost, reproductive fitness may be affected, however, this appears to be almost exclusive to triazine resistant species which consistently suffer fitness penalties (Jasieniuk *et al.*, 1996). The current status of weed species resistance to herbicides throughout the world reflects the interplay of these mentioned factors (Powles *et al.*, 1997).

Forty years of herbicide use has selected for increased resistance within formerly susceptible weed species (Holt *et al.*, 1993). The primary reason for the selection of resistant biotypes is the farming practices that have developed since the discovery of selective herbicides (Shaner, 1995). In most cases, resistance has occurred because herbicides of the same mode of action were used repeatedly in intensive agricultural or horticultural systems. Crop monoculture and reduced cultivation practices dominated, whilst IWM strategies were rarely practiced. Herbicides have almost exclusively been used in these systems to achieve the high level of weed control necessary (Moss and Rubin, 1993).

Herbicide resistance in weed species was predicted by Abel (1954), however, it was not until the late 1960's that it became apparent. Ryan (1970) in Washington State, USA reported that the repeated application of simazine in a conifer nursery selected for a *Senecio vulgaris* population that became resistant to simazine and atrazine. During the 1970's, resistance to dintroanilines, bipyridiliums, and pyridazolinones

was discovered in a small number of species over a limited area. However, throughout the 1980's there was a dramatic increase in the number of resistant weed species and biotypes. Widespread resistance was confirmed to a variety of herbicides, including; ACCasc inhibitors, ALS inhibitors, amides, amitrole, arsenicals, benzonitriles, carbamates, picloram, substituted ureas, and uracils (LeBaron, 1991). Furthermore, biotypes of several species have developed cross and multiple resistance. The most notable examples include *L. rigidum* and *Alopecurus myosuroides* (Hall *et al.*, 1994). Heap (1997) in a recent international survey, reported that 183 herbicide resistant weed biotypes have been found in 42 countries.

2.5.3 Genetics of herbicide resistance in *Avena* spp.

Herbicide resistance in weeds may be attributed to one or more mechanisms; reduction in herbicide uptake and translocation, enhanced herbicide metabolism (detoxification), sequestration or compartmentation of the herbicide, or a modified target site.

Target site based resistance is the most commonly documented mechanism of resistance in weed species, and the most frequently found form in *Avena* spp. Studies in Australia, Canada and the United States have demonstrated that wild oat populations resistant to ACCase inhibitors consistently have altered ACCase enzymes (Barr *et al.*, 1992; Maneechote *et al.*, 1994; Murray *et al.*, 1995; Seefeldt *et al.*, 1996a). In addition, Maneechote *et al.* (1997) determined a modified ACCase enzyme and enhanced metabolism which both contributed to resistance in an *A. ludoviciana* biotype. Maneechote (1995) also identified an *A. ludoviciana* biotype which gained resistance through reduced herbicide translocation of diclofop. In Canada, Devine *et al.* (1993) determined that resistance of an *A. fatua* biotype was correlated with repolarisation of the plasma membrane following diclofop treatment. However, subsequent studies concluded that resistance was due primarily to an altered ACCase (cited by Seefeldt *et al.*, 1996b). Given *Avena* spp. resistant to ACCase inhibitors possess a variety of resistance mechanisms, it is not surprising that cross resistance patterns have occurred, making control of resistant populations with alternative herbicides difficult.

For herbicide resistance to evolve to detectable levels in a weed population, the resistance trait must be heritable (Murray *et al.*, 1995). Various studies have indicated that the inheritance of ACCase inhibitor resistance in *Avena* spp. biotypes is due to a single partially dominant or single dominant nuclear gene (Barr *et al.*, 1992; Murray *et al.*, 1995; Murray *et al.*, 1996; Zanin and Lucchin, 1996). Given single gene inheritance, resistance can evolve rapidly because of the relative ease with which resistance alleles are established within a population, and because resistance alleles are not lost in the heterozygous genotypes when the herbicide is applied at recommended field dosages (Murray *et al.*, 1996).

2.5.4 Herbicide tolerance in *Avena* spp.

It has long been recognised that wild oat populations previously unexposed to herbicides exhibit considerable variation in their response to avenacides, both between and within populations. *Avena* spp. accessions have displayed a natural tolerance toward; propham, diallate, triallate, barban, difenzoquat, flamprop, MSMA and diclofop (Rydrych and Seeley, 1964; Jacobsohn and Andersen, 1968; Jana and Naylor, 1982; Miller *et al.*, 1982; Price *et al.*, 1983; Somody *et al.*, 1984; Thai *et al.*, 1985; Efthimiadis *et al.*, 1993).

Avena spp. tolerance to herbicides can relate to morphological characteristics. Rydrych and Seeley (1964) reported that *A. fatua* strains with grey glabrous lemmas and non-dormant seed were generally more tolerant to propham than those with brown pubescent lemmas and dormant seed. Whilst Price *et al.* (1985) determined the level of genetic variation for herbicide response to be associated with genetic variation for morphological and enzymatic loci. Conversely, Jacobsohn and Andersen (1968) found no relationship between morphological characteristics and *A. fatua* response to diallate, triallate or barban. Somody *et al.* (1984) working with *Avena* spp. accessions from the United States, found tolerance to several herbicides was not due to low leaf surface area, as the tolerant populations usually had greater leaf surface area.

Research by Jana and Naylor (1982) and Thai *et al.* (1985) determined that continuous treatment of *A. fatua* populations with triallate produced increased levels of tolerance to the herbicide. These studies showed that genetic variability of wild oat

populations gives the capacity for adaptation to the sustained application of herbicides.

2.5.5 Herbicide resistance in *Avena* spp.

Resistance in *Avena* spp. has been recorded to a variety of herbicides and herbicide groups in seven countries (Zanin and Lucchin, 1996; Heap, 1997), primarily Canada (Heap *et al.*, 1993; O'Donovan *et al.*, 1994), United States (Malchow *et al.*, 1993; Seefeldt *et al.*, 1994) and Australia (Mansooji *et al.*, 1992). In Australia, resistance has been reported in both *A. fatua* and *A. ludoviciana* to the ACCase inhibitors, but not to any other herbicide group (Holtum, 1992). Of the two species, a greater number of resistant *A. fatua* populations have evolved world-wide, since *A. ludoviciana* rarely occurs in North America.

Resistance patterns vary considerably between wild oat populations (Mansooji *et al.*, 1992), however, there is no evidence to suggest that the general patterns for resistance differ between *A. fatua* and *A. ludoviciana* (Holtum, 1992). Nevertheless, it is worth noting the results of a survey undertaken in 1993 in the UK. Forty six *A. fatua*, eight *A. ludoviciana* and five populations which contained both species were collected from winter cereal fields where a problem with chemical control was suspected. All were screened for resistance to fenoxaprop-ethyl. Of the 59 populations tested, three were found to be resistant and all were *A. ludoviciana*. This was surprising, as the majority of samples tested were *A. fatua*. Interestingly, one of the resistant *A. ludoviciana* biotypes was a component of a mixed population. Only the *A. ludoviciana* plants were resistant (including to diclofop-methyl and fluazifop-*p*-butyl), whilst the *A. fatua* component was susceptible (S. Moss, pers. comm.).

The variation and extent of resistance in *Avena* spp. indicates that resistance probably develops *in situ* and therefore the extent of resistance in populations varies from field to field (Mansooji *et al.*, 1992). Biotypes resistant to the ACCase inhibitors (especially diclofop-methyl) constitute the majority of resistant populations world-wide, however, resistance in *Avena* spp. has also developed to several non-ACCase inhibitors.

2.5.5.1 Resistance to ACCase inhibitors

In the late 1970's, diclofop-methyl was the first ACCase inhibitor commercialised. This herbicide provided unprecedented efficacy and crop safety. Diclofop-methyl and subsequently released ACCase inhibitors became, and still are, widely used for grass control in world agriculture (ACCase inhibitors currently account for more than 5% of global herbicide sales (Heap, 1997)). However, repeated exposure to herbicides from this group soon resulted in the appearance of resistant populations. The first case of resistance to an ACCase inhibitor was documented in Australia in *L. rigidum* (Heap and Knight, 1982). Within several years resistance was confirmed in *A. fatua* and *A. ludoviciana*. The first documented case of resistance in *Avena* spp. was in 1985, when a population of *A. fatua* displayed resistance to diclofop-methyl in South Africa (LeBaron and McFarland, 1990). Also in 1985, concern was expressed in Western Australia when a population of *A. fatua* which for six years had been annually exposed to diclofop-methyl, was not controlled by a further application. The biotype was resistant only to diclofop-methyl and had a LD_{50} (dose of herbicide required to kill 50% of plants), three fold greater than that of a susceptible biotype (Boutsalis *et al.*, 1990; Piper, 1990). The first resistant *A. ludoviciana* population was detected in Australia and exhibited high levels of resistance to diclofop-methyl and several other APP's, but low resistance to the CHD's (Mansooji *et al.*, 1992). It was selected with diclofop-methyl and fluazifop-butyl.

The most significant cases of ACCase inhibitor resistance in *Avena* spp. have been in North America, where *A. fatua* populations have developed resistance to APP's and CHD's. Resistance is documented in Oregon, USA (Seefeldt *et al.*, 1994; Seefeldt *et al.*, 1996b) and western Canada (Joseph *et al.*, 1990; Heap *et al.*, 1993). In Canada, hundreds of *A. fatua* populations have been identified that are resistant to ACCase inhibitors, the majority in Manitoba. In 1994, a random survey of Manitoba cropping regions, where ACCase inhibitors were known to be used on more than half of the fields, determined that 20% of the wild oat populations were resistant to ACCase inhibitors (Morrison and Bourgeois, 1995). Most Canadian biotypes are resistant to both herbicide classes of the ACCase inhibitors (Devine and Shimabukuro, 1994), whilst resistance has also developed to APPs and CHD's in an *A. ludoviciana* biotype in the UK (S. Moss, pers. comm.).

The number of herbicide applications to which ACCase inhibitor resistant biotypes have been exposed vary, ranging from less than five to over 10 (Holtum, 1992; Heap *et al.*, 1993). However, *Avena* spp. populations with higher numbers of exposures to the ACCase inhibitors are more likely to develop resistance (Heap *et al.*, 1993; Mansooji, 1993; Bourgeois and Morrison, 1997).

Four general patterns of ACCase inhibitor resistance in *Avena* spp. are reported throughout the world. In Australia, two initial patterns of resistance have been recorded; resistance only to diclofop-methyl or; a high resistance to all APP's and a low resistance to CHD's. Whilst in Canada, these patterns along with; a high resistance to APP's and CHD's or; a high resistance to CHD's and low resistance to APP's have been documented (Holtum, 1992). The levels of resistance to CHD's reported in Australian populations are not considered agronomically relevant, since CHD's consistently remain effective when used at recommended rates. Although high resistance to CHD's has not yet been documented in Australia, given the experience overseas it will undoubtedly appear.

2.5.5.2 Resistance to non-ACCase inhibitors

Resistance in *Avena* spp. has developed to several non-ACCase inhibitors. The most noted example is to the pre-emergent herbicide, triallate. In the late 1970's several *A. fatua* biotypes resistant to triallate were identified in western Canada, with some showing cross resistance to diclofop-methyl (Thai *et al.*, 1985). However, it has only been in recent years that widespread resistance to triallate has developed.

A. fatua resistant to triallate has been reported on numerous farms in Alberta, Canada. Compared to ACCase inhibitor resistance, triallate resistance has been slow to develop, as in most fields, triallate was continuously used for at least 15 years before resistance was detected. All populations resistant to triallate also exhibited resistance to difenzoquat (an unrelated herbicide to triallate), with some biotypes exhibiting cross resistance (O'Donovan *et al.*, 1994). A re-examination of several resistant biotypes by Blackshaw *et al.* (1996) revealed they were susceptible to numerous alternative herbicides representing four groups, including the ACCase inhibitors. Many *A. fatua* populations resistant to triallate and difenzoquat have also developed after persistent use of triallate in Montana, USA (Malchow *et al.*, 1993).

Resistance to diallate was also found (Kern *et al.*, 1996). Such is the magnitude of triallate resistance in Montana, a 1993 survey undertaken in a major barley growing region revealed that 94% of fields contained resistant *A. fatua* (Davidson *et al.*, 1996).

The only other known examples of resistance in wild oats to non-ACCase inhibitors is for imazamethabenz-methyl (an ALS inhibitor) and two different isomers of flamprop. In 1994, two *A. fatua* populations from Manitoba were identified as being resistant to both imazamethabenz-methyl and flamprop-methyl. In each case selection intensity was generally similar, as imazamethabenz-methyl and flamprop-methyl were only applied once, along with herbicides from several other herbicide groups. Each population was also resistant to fenoxaprop-*p*-ethyl (Morrison and Bourgeois, 1995; Morrison *et al.*, 1995). Recently, two more *A. fatua* populations from Manitoba were identified as resistant to flamprop-methyl (I. Morrison, pers. comm.). In the UK, an *A. ludoviciana* population has also developed resistance to flamprop. This biotype is resistant to flamprop-*m*-isopropyl, and imazamethabenz-methyl, along with several ACCase inhibitors (S. Moss, pers. comm). The extent and type of herbicides used in the selection process are not known.

Unlike the triallate resistant biotypes of Alberta and Montana which have generally taken at least 15 years to develop, the rapid occurrence of multiple resistance after selection with imazamethabenz-methyl and flamprop-methyl is of major concern. Undoubtedly the often rapid and diverse evolution of resistance patterns in *Avena* spp. necessitates a more integrated approach to management.

2.5.6 Adoption of integrated strategies for *Avena* spp. management in southern Australia

IWM is essential for sustainable weed control. The goals of an IWM system should be to reduce the movement of weed seed into the soil and to reduce the impact of weeds on the crop to an economically acceptable level (O'Donovan, 1995). In addition, the integration of cultural control methods into crop rotations, coupled with the use of effective alternative herbicides, will aid in reducing the herbicide resistant weed burden (Matthews, 1994). Herbicide rotation and reduced reliance on

herbicides through cultural control strategies, remain the principal means of dealing with herbicide resistance (Morrison and Friesen, 1996).

2.5.6.1 Herbicide rotation

Rotation between chemical groups slows the onset of resistance to any single group. Upon discovery of ACCase inhibitor resistant *A. fatua* in Canada, the early extension emphasis was placed on herbicide rotation to manage resistance (Goodwin, 1994). Likewise, many farmers in southern Australia have relied on herbicide rotation to initially manage the problem, especially in continuous cropping systems where there are few effective cultural control options (discussed below).

Because herbicide resistance in wild oats is currently confined to the APP's in Australia, the rotation to other chemical groups (including CHD's), is imperative to minimise further APP resistance. Evidence this is occurring comes from increased sales of major non-ACCase inhibitors. For example, sales of triallate and flamprop-methyl have steadily increased in southern Australia over the last few years - partially due to the threat of ACCase inhibitor resistance (M. Edmondson, pers. comm.; J. Holmes, pers. comm.). Unlike *L. rigidum* in southern Australia, there have been only low levels of CHD resistant *Avena* spp. reported, and recommended rates of CHD's remain effective on most APP resistant populations. Thus, the usefulness of CHD's (and other herbicide groups) to minimise complex resistance patterns may be prolonged through prudent herbicide choice and use.

However, sole reliance on herbicide rotation to avert resistance is not recommended for *Avena* spp. control. Experience from overseas demonstrates that simply rotating out of one chemical class into another, does not prevent CHD, multiple or cross resistance in wild oats (Heap *et al.*, 1993; Seefeldt *et al.*, 1994; Morrison and Bourgeois, 1995). Although CHD and cross resistance in *Avena* spp. have not been documented in Australia, these patterns will undoubtedly appear unless avenacides are integrated with cultural control measures.

2.5.6.2 Cultural control

Farmers in southern Australia are advised to adopt cultural strategies to minimise herbicide resistant wild oats, but in reality few would. This is due to most avenacides

being highly effective on APP resistant wild oats and few cultural options are economically attractive and or sufficiently effective to warrant adoption. Cutting crops and selling them for hay currently provides good returns. However, the early shedding habit of wild oats requires cutting to be undertaken relatively early to prevent seed production, resulting in reduced hay yield. The practices of windrowing and weed seed collection at harvest are poor wild oat control measures. Whilst, the burning of crop residues is considered to be variable in its effectiveness. Practices which incorporate a pasture phase, green manure crop or winter fallow in a crop rotation provide the opportunity to prevent wild oat seed production and significantly deplete seed banks. However, these options are currently perceived as uneconomical.

Traditionally, southern Australia farmers incorporated a pasture phase into their rotation. However, in recent years a relative decline in the value of livestock production, coupled with more favourable economic returns from grain enterprises have caused many farmers to pursue prolonged periods of continuous cropping. Since few cultural strategies are utilised for wild oat control in these cropping dominated systems, heavy pressure is placed on selective herbicides for weed control, which increases the potential of herbicide resistance. Here-in lies the challenge - to manage wild oats that are developing or have developed resistance to herbicides, but continue cropping intensively.

2.6 Conclusion

Avena spp. are very well adapted as crop weeds and their continuing importance world-wide indicates the problems inherent with current control methods. In addition, the control of wild oats have been complicated by the development of herbicide resistance, further ensuring their persistence.

A range of IWM techniques can be utilised for wild oat management in southern Australian farming systems. These may include; cultivation, delayed seeding, increased crop competition, windrowing, weed seed collection at harvest, crop stubble burning, green manuring, hay making, silage, crop and pasture rotation and herbicide application. Herbicides are the favoured option as they provide immediate, cost effective control and farmers are generally satisfied with the efficacy achieved.

However, it is important that cultural strategies also be incorporated into an integrated system to help slow the onset of herbicide resistance.

The following chapters of this thesis detail various studies aimed at determining appropriate strategies for managing *Avena* spp. in southern Australian farming systems. Cultural and chemical control techniques are discussed, as are findings from several seed bank experiments. Survey results detailing the incidence of, and extent of herbicide resistance in *Avena* spp. for a major cropping region of southern Australia are initially reported.

Chapter 3

3. The incidence of, and extent of herbicide resistance in *Avena* spp. for the mid-north of South Australia

3.1 Introduction

Wild oats probably rank as the most widespread and important weeds of Australian cropping systems. The main weedy species include; *A. fatua*, *A. ludoviciana* and *A. barbata* (Medd, 1996b). The relative incidence and distribution of each *Avena* species differs throughout Australia (see 2.2.3). This can be due to a variety of factors. In Western Australia, Paterson (1976b) found that *A. fatua* predominated in the drier and warmer regions of the state's cropping belt, and *A. barbata* in the cooler and wetter areas. Paterson *et al.* (1976b) suggested this was largely due to differing responses to temperature and daylength (photoperiod) of the two species. In addition, Paterson (1976b) determined that *A. fatua* occurs more commonly on fine textured loams and *A. barbata* on coarse sands. In Queensland, Watkins (1967) found a higher proportion of *A. ludoviciana* to *A. fatua* on heavy black earths, compared to lighter brigalow soils. Different germination requirements of *A. fatua* and *A. ludoviciana* (Quail and Carter, 1968) may also allow one species to predominate in a particular region.

Apart from environment, farming practice can also influence wild oat species distribution. McNamara (1972) in New South Wales, claimed *A. fatua* was more prevalent in early sown crops and *A. ludoviciana* in late sown crops. Although this is probably a function of timing of emergence (due to the differing temperature requirements for germination of each species), it suggests that delaying the date of seeding would select for *A. ludoviciana*, given a greater proportion of *A. fatua* seedlings would be killed before sowing. Indeed, management will greatly influence the incidence of weed species, irrespective of any environmental influences.

According to Medd (1996b), there are anecdotal indications that the species distribution of *A. fatua* and *A. ludoviciana* in Australian cropping areas are changing,

though there have been no recent surveys of either inter- or intra-specific genetic variation. In South Australia, Heap and Stephenson (1986) suggest *A. fatua* is more prevalent than *A. ludoviciana*, but gave no supporting evidence detailing the relative abundance of each species.

The mid-north of South Australia is considered one of the state's most productive cropping regions. In 1996, 368,000 tonnes of cereal grain was produced, this constituting 7% of South Australia's cereal tonnage for the year (S. Hogg pers. comm.). The choice of crop is largely dependent on rainfall and soil type, but wheat, barley, canola and pulses (eg. field peas) are commonly grown. Rainfall and temperature distribution are representative of a Mediterranean type climate, with hot dry summers and cool wet winters. Average annual rainfall ranges from 250 to 600 mm and the normal growing season extends from April to October. In the mid-north of South Australia, *Avena* spp. are categorised as the most serious weeds of farming systems (Mayfield and Edwards, 1992), with both *A. fatua* and *A. ludoviciana* occurring, however, their relative abundance and distribution throughout the region remains unknown.

Herbicide resistance in *Avena* spp. is a developing problem in southern Australia. Several studies have been undertaken to determine the incidence of resistance in wild oats to the ACCase inhibitors. A survey of north eastern Victoria determined that 6% of 1992 cropping fields contained diclofop-methyl resistant *Avena* spp. (Walsh, 1995), whilst in southern New South Wales the level of diclofop-methyl resistant wild oats had marginally increased from 3% in 1991 to 5% in 1994 (J. Broster pers. comm.). In addition, the Victorian study (Walsh, 1995) determined that resistance was more likely to occur in areas where intensive cropping rotations with stubble retention systems and early time of sowing practices were employed. Resistance in *Avena* spp. has been confirmed in the mid-north of South Australia (J. Matthews pers. comm.) but the extent of the problem is unknown.

This chapter reports the results of a study undertaken to determine the occurrence and species incidence of wild oats, and extent of herbicide resistance in *Avena* spp. for a major cropping region of southern Australia. It was accomplished by a random field survey of cropping fields in the mid-north of South Australia. *Avena* spp. seed

samples were screened for resistance to diclofop-methyl - the most widely used ACCase inhibitor in southern Australian farming systems.

3.2 Materials and Methods

3.2.1 Sampling procedure

From 25/10/93 to 16/11/93, *Avena* spp. panicles were collected from randomly selected fields where a grain crop was being grown. During this time, crops were at late maturity and *Avena* spp. plants were about to shed their seed. The fields were located within a region approximately 160 x 50 km, ranging from Roseworthy (34°32' S, 138°45' E) in the south, to Yongala (33°02' S, 138°45' E) in the north (Figure 3.1). This area forms a major part of the mid-north cropping zone of South Australia, the majority receiving an average annual rainfall greater than 400 mm.

Fields throughout the survey area were randomly selected by stopping every five km along a road and sampling the adjacent field. Each field was surveyed by the author and Mr. R. Llewellyn. Over a minimum of five minutes, wild oat panicles were collected at random intervals up to 200 m into the field. Field corners, headlands and a zone 15 m from the fence-line were avoided as these areas are not usually representative of a field as a whole. The crop type was recorded for each field along with wild oat infestation levels, which were visually estimated by each person and a score agreed at the end. When sampling, patchiness of *Avena* spp. was frequently observed within fields, and was taken into account when estimating the level of infestation. A score from 0 (no plants observed) -5 (high infestation) was determined, which was equated to an estimated *Avena* spp. plant density. The following categories were recognised; 0 = no plants observed, 1 = <0.05 plants/m^2, 2 = 0.05-10 plants/m^2, 3 = 11-20 plants/m^2, 4 = 21-30 plants/m^2, 5 = >31 plants/m^2. In total, 236 fields were surveyed.

All seed samples were allowed to after-ripen at ambient temperatures (under shelter) at Roseworthy until July 1994, when they were threshed and cleaned. Before threshing, all populations were classified as *A. fatua*, *A. ludoviciana* or both (*A. fatua* and *A. ludoviciana*). Identification between species was based on the criteria cited in 2.2.4 (Table 2.1). There were no *A. barbata* seeds detected in any of the samples.

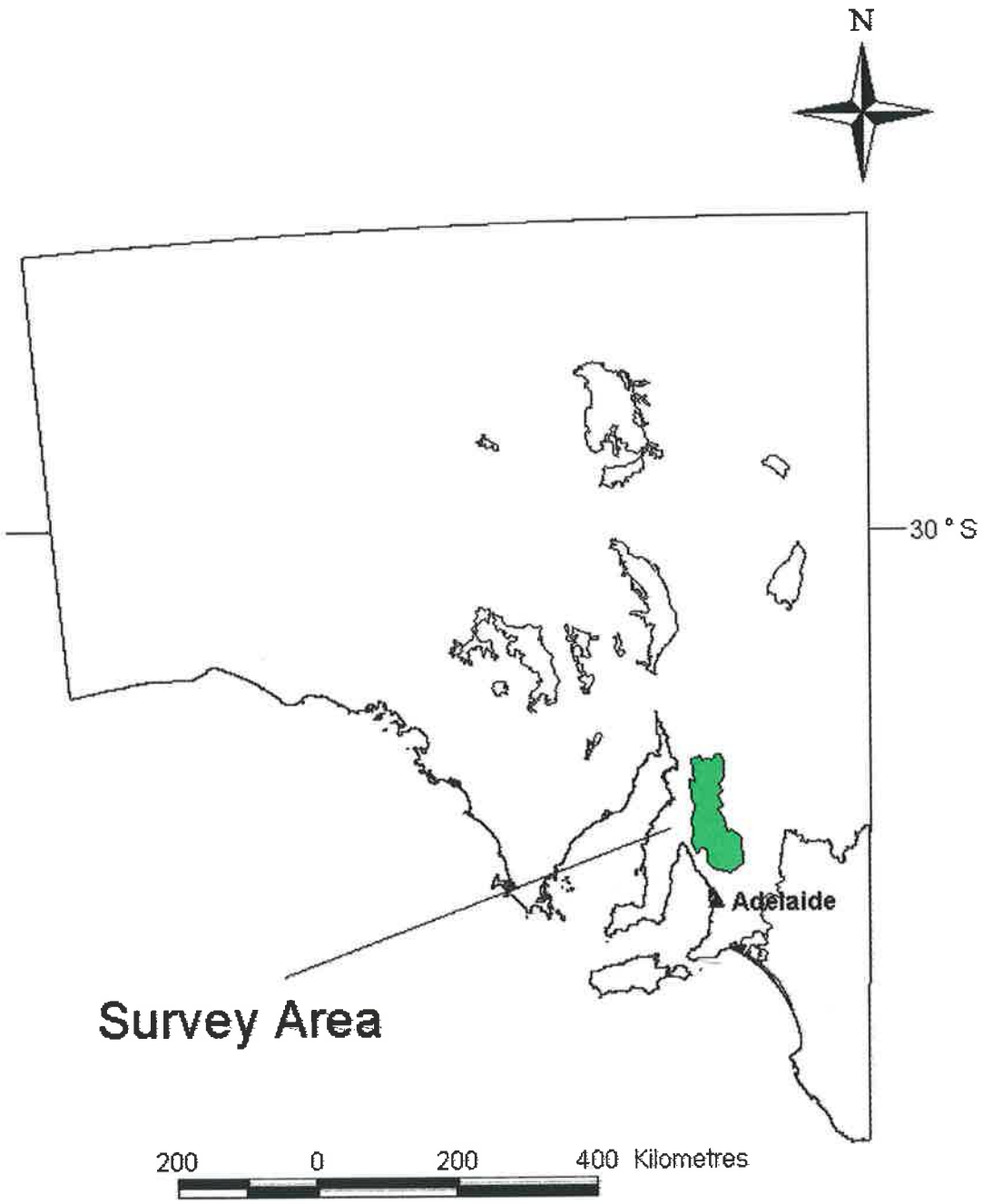


Figure 3.1 Area located in South Australia surveyed for *Avena* species.

3.2.2 Herbicide resistance testing

Wild oat seeds from each sample were pre-germinated and the seedlings grown out before being treated with diclofop-methyl. To encourage germination, seeds were dehusked and punctured at the embryo end with a fine dissecting needle. They were then placed in containers containing a solution of 0.6% agar and 0.1% thiram, moistened with water and transferred to a refrigerator set at 4°C for a period of seven days for vernalisation. Samples were then placed in a laboratory growth chamber maintained at a 12 hour, 15°C light / 12 hour, 10°C dark regime. Soon after leaf emergence, seedlings were transplanted into 18 x 10 x 6 cm plastic containers containing recycled potting soil. A maximum of 10 seedlings were sown into each container after which they were moved outdoors and watered at regular intervals during the experimental period. At the Z12-Z14 (2 to 4 leaf) growth stage (Zadoks *et al.*, 1974), the plants were sprayed with the recommended rate of diclofop-methyl (563 g a.i./ha) for Australian broadacre crops. To ensure good herbicide coverage, treatment was undertaken twice at the half rate and a non-ionic surfactant (0.25% Chemwet 1000®) was added to the herbicide solution. A hand-held boom sprayer that delivered 136 l/ha of water at a pressure of 275 kPa was used. A minimum of three replicates per population were sprayed, including a wild oat population known to be susceptible to diclofop-methyl, to check herbicide efficacy.

Testing for herbicide resistance was undertaken between the months of July and September, in 1994 to 1996. This was necessitated as some populations produced low germination in the first and or second year of testing, and a minimum of 30 plants were required to be sprayed to ensure an adequate sample size. A total of 133 populations were treated that reached this criteria. Twenty three days after spraying, seedlings were classified as either susceptible or resistant and a survival percentage derived for each population. Susceptible plants showed severe necrosis and were killed within two to three weeks post herbicide application, whilst resistant plants showed very little, or no symptoms of herbicide injury. Any population with a greater level than 15% of resistant seedlings was regarded as exhibiting an agronomically relevant level of resistance.

3.2.3 Analysis

The distribution of *Avena* spp. and level of herbicide resistance throughout the survey area were plotted using Arcview 3.0 (Environmental Systems Research Institute, Redlands, USA). Statistical analysis was carried out to determine if any relationship existed between the following comparisons; *Avena* species x crop, *Avena* species x infestation level, *Avena* spp. infestation level x resistance level, and *Avena* species x resistance level. Method of analysis was either the Kruskal-Wallis one-way analysis of variance, or contingency tables tested by the Pearson chi-square method.

3.3 Results

3.3.1 Occurrence and distribution of *Avena* spp. in the mid-north of South Australia

Of the 236 cropping fields randomly surveyed throughout the mid-north of South Australia, wild oats were noted in 212 fields - an incidence of 90% (Table 3.1). Visual assessment of *Avena* spp. infestation levels indicated that 33% of the fields contained greater than 10 plants/m^2 (Table 3.1).

Table 3.1 Field infestation levels of *Avena* spp. in the mid-north of South Australia.

Infestation level (plants/m^2)	0	<0.05	0.05-10	11-20	21-30	>31
Fields (%)	10	27	30	23	6	4
Fields (nos.)	24	64	70	54	15	9

Avena spp. samples were collected from a variety of cereal, pulse and oilseed crops, however, 87% of samples came from wheat and barley crops (data not presented). Each wild oat sample collected was classified into species, with *A. ludoviciana* dominating, although a similar percentage of samples comprised both *A. fatua* and *A. ludoviciana* seed (Table 3.2). Statistical analysis determined there was no association between *Avena* species and crop species ($P>0.05$, data not presented).

Table 3.2 The incidence of *Avena* species in the mid-north of South Australia.

	Fields	
	(%)	(nos.)
A. fatua	17	33
A. ludoviciana	44	87
Both[†]	39	77

[†]Samples contain both *A. fatua* and *A. ludoviciana* seed.

Further statistical analysis determined there was no association between *Avena* species and infestation level within each field (Table 3.3).

Table 3.3 The infestation levels of wild oat populations from the mid-north of South Australia, relative to *Avena* species.

	Fields (%)				
Infestation level (plants/m^2)	>0-0.05	0.05-10	11-20	21-30	>31
A. fatua	37	29	20	3	11
A. ludoviciana	24	38	28	8	2
Both[†]	30	29	28	9	4

[†]Samples contain both *A. fatua* and *A. ludoviciana* seed.
Kruskal-Wallis analysis based on a sample size of 33 *A. fatua*, 87 *A. ludoviciana* and 77 populations comprising both species. There was no significant difference between *Avena* species and field infestation levels (chi-square *P*-value = 0.31).

Both species of wild oats were widely distributed throughout the survey area. Visual assessment of Figure 3.2 suggests that neither *A. fatua* or *A. ludoviciana* dominated within any part of the surveyed area.

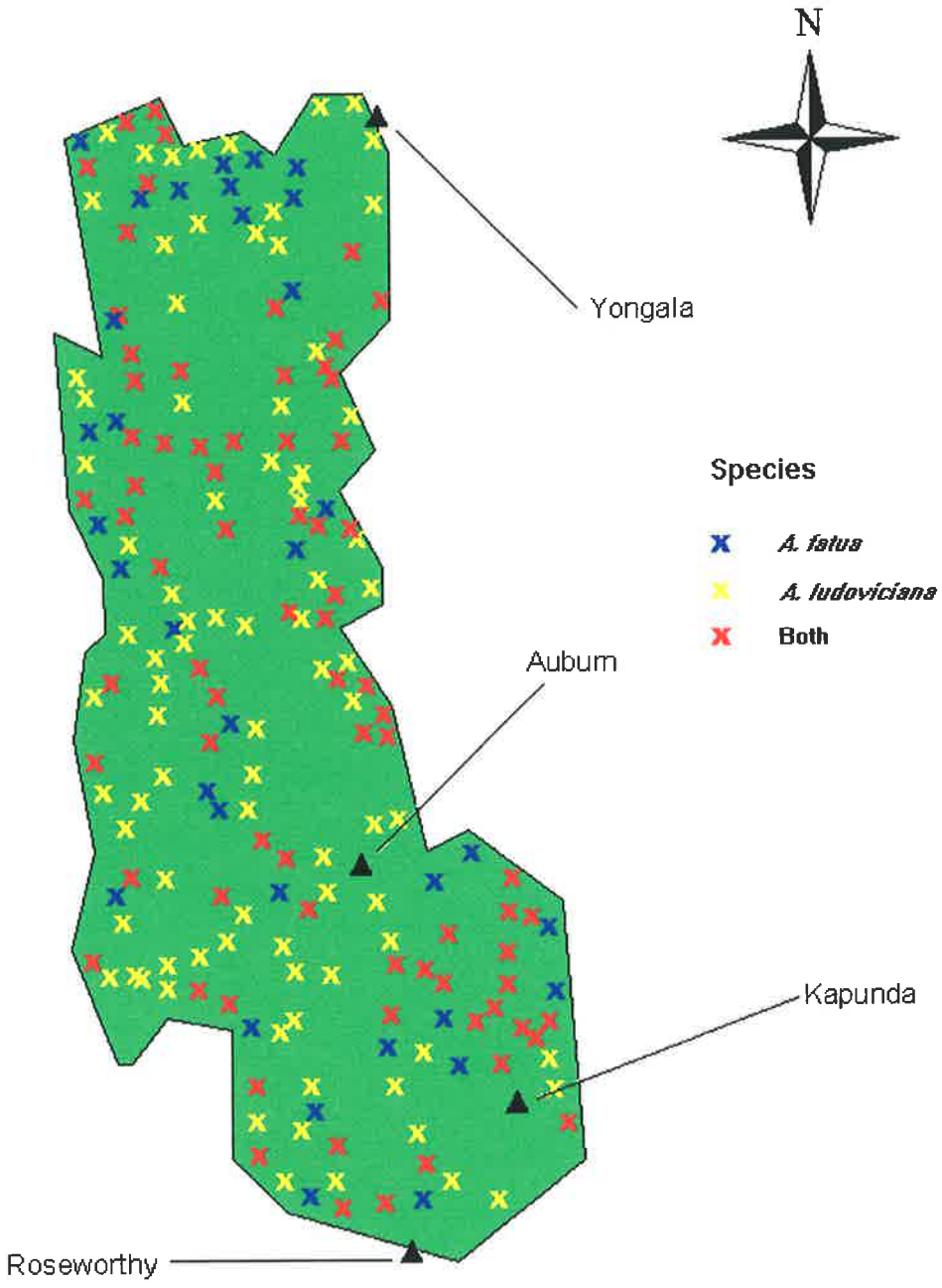


Figure 3.2 Distribution of *Avena* species throughout the mid-north of South Australia.

3.3.2 Extent of herbicide resistance in *Avena* spp. in the mid-north of South Australia

Varying levels of resistance in *Avena* spp. to diclofop-methyl were detected throughout the survey area. Of the 133 wild oat samples evaluated, 27% showed some degree of resistance, although only 2.3% of fields exhibited a level of agronomic relevance (greater than 15% seedling survival) (Table 3.4).

Table 3.4 The survival of *Avena* spp. seedlings from populations in the mid-north of South Australia, after treatment with 563 g a.i./ha of diclofop-methyl.

Seedling survival (%)	0	>0-<5	>5-<15	>15
Populations (%)	72.9	17.3	7.5	2.3
Populations (nos.)	97	23	10	3[†]

[†]The seedling survival of the three populations in the '>15' group were 15-, 21- and 23% respectively.

The distribution of resistance in *Avena* spp. throughout the survey area is depicted in Figure 3.3. Visual assessment of Figure 3.3 indicates that higher levels of resistance to diclofop-methyl occurred mainly in the southern region of the survey area, however, resistant populations were located throughout the sampling area.

There was no association (P>0.05) between the infestation level of wild oats and level of resistance to diclofop-methyl (Table 3.5).

Table 3.5 The mean survival of *Avena* spp. seedlings (after treatment with 563 g a.i./ha of diclofop-methyl) from populations in the mid-north of South Australia, relative to the level of field infestation.

Infestation level (plants/m^2)	<0.05	0.05-10	11-20	21-30	>31
Seedling survival (%)	1.8	1.0	2.1	1.1	1.1

Chi-square analysis based on a sample size of 133 populations. There was no significant difference between field infestation levels in their degree of seedling survival (chi-square P-value = 0.70).

Analysis was also conducted to determine the likelihood of association between *Avena* species and level of resistance to diclofop-methyl, however, no significant difference between species was found (Table 3.6).

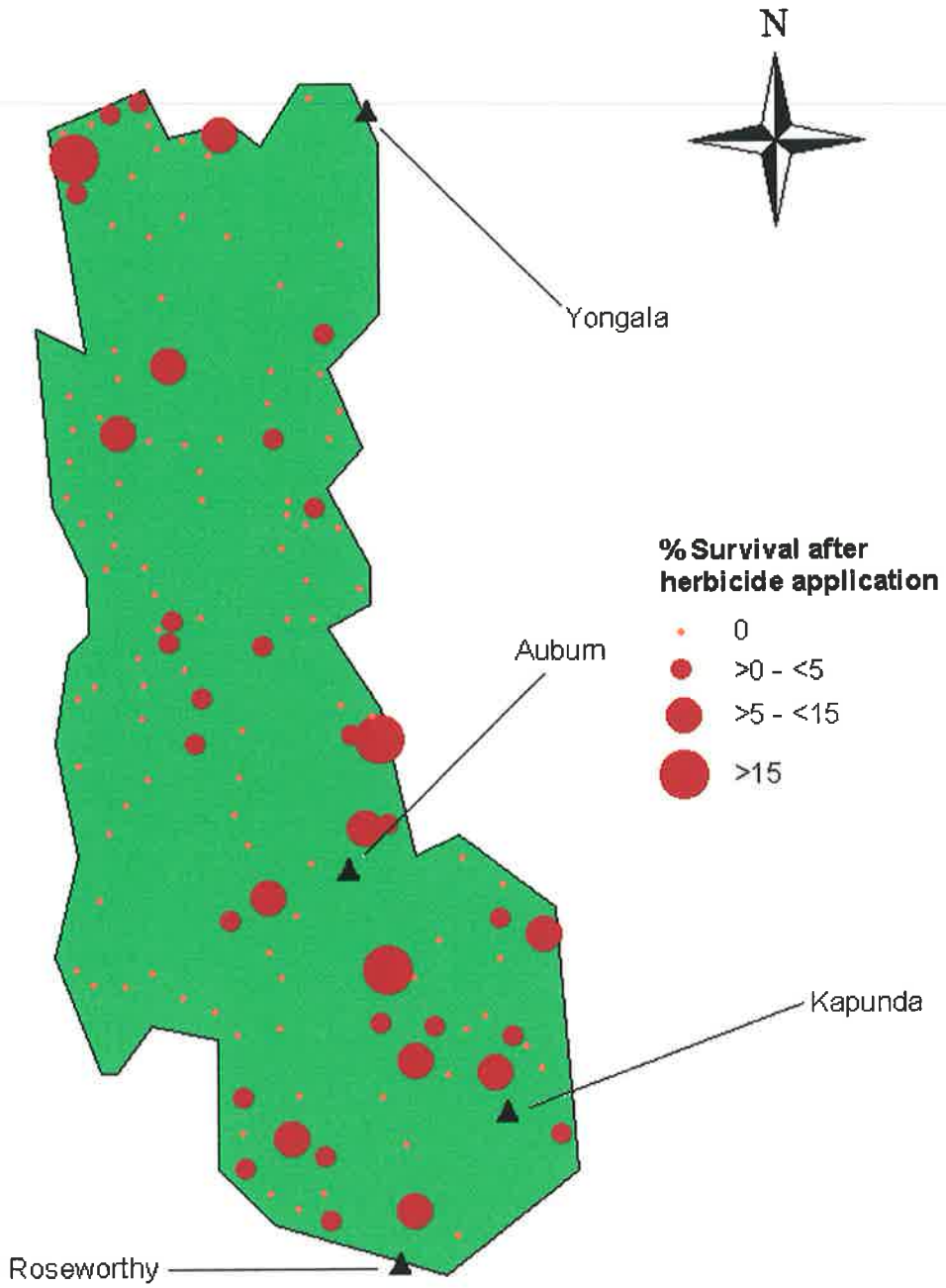


Figure 3.3 Distribution and level of herbicide resistant *Avena* spp. (to diclofop-methyl at 563 g a.i./ha) throughout the mid-north of South Australia.

Table 3.6 The mean survival of seedlings (after treatment with 563 g a.i./ha of diclofop-methyl) from populations in the mid-north of South Australia, relative to each *Avena* species.

	Seedling survival (%)
A. fatua	1.3
A. ludoviciana	0.8
Both[†]	2.3

[†]Samples contain both *A. fatua* and *A. ludoviciana* seed.
Chi-square analysis based on a sample size of 20 *A. fatua*, 55 *A. ludoviciana* and 58 populations comprising both species. There was no significant difference between *Avena* species in their level of seedling survival (chi-square *P*-value = 0.09).

3.4 Discussion

3.4.1 Incidence of, and extent of herbicide resistance in *Avena* spp.

A survey conducted at late crop maturity throughout the mid-north of South Australia found that 90% of cropping fields contained *Avena* spp., with one third of fields containing relatively high infestation levels (>10 plants/m^2) (Table 3.1). In addition, wild oats were evenly located throughout the sampling area (Figure 3.2). This high incidence and wide geographical distribution concurs with Mayfield and Edwards (1992), who concluded (from a mail survey) that *Avena* spp. are the most serious weeds of farming systems in the mid-north of South Australia. Two species of wild oats were collected from the survey region; *A. fatua* and *A. ludoviciana*, with the latter predominating, but with a substantial number of fields containing both species (Table 3.2). This is the first survey of its type where the proportion of *Avena* species has been documented within a specific region of South Australia. While the survey area represented only about 6% of the state's cropping zone (S. Hogg pers. comm.), there was no support for the contention of Heap and Stephenson (1986) that *A. fatua* is the dominant wild oat species in South Australia.

While incidence of *A. ludoviciana* was greater than *A. fatua*, both species were widely distributed, with neither species dominating in any part of the sampling area (Figure 3.2). The occurrence of each species may be linked to environmental influences, such as rainfall, temperature, photoperiod or soil type. However, in this survey, fields were not tested for soil type, nor was climatic data determined for each

sampling site. As crop management practice (eg. time of sowing, herbicide application, crop rotation) also affects the relative incidence of weed species, it was not possible to determine if the presence of *A fatua* and *A. ludoviciana* were correlated with particular environmental or management factors.

Throughout southern Australia both *A. fatua* and *A. ludoviciana* have traditionally been treated as one, ie. 'wild oats', irrespective of any differences between the species. Using the collected data, this rationale can be tested for several parameters. Analysis confirmed that each species had similar infestation levels within fields (Table 3.3) and did not differ in their level of resistance to diclofop-methyl (Table 3.6). However, to confirm if the species distribution of *Avena* spp. are changing (as speculated by Medd (1996b)), further sampling would need to be undertaken within the survey area in the future. While 39% of fields contained *A. fatua* and *A. ludoviciana* plants (Table 3.2), and these fields were evenly located throughout the sampling area (Figure 3.2), it is not possible to determine if wild oat species have colonised a greater percentage of fields in the region. Effective *Avena* spp. control in 1993 (year the survey was conducted) would reduce wild oat observation, but seed banks may still exist. Since *Avena* spp. do not naturally spread over long distances (Thurston and Phillipson, 1976), it is most probable that either *A. fatua* and or *A. ludoviciana* entered fields via contaminated grain or through other dispersal means (see 2.2.5).

The survey was undertaken just prior to harvest and therefore represents *Avena* spp. plants which may have survived earlier herbicide treatment(s). Of the populations tested for resistance to diclofop-methyl, it was found that approximately a quarter displayed some resistance, while 2.3% exhibited a significant level (Table 3.4). This (2.3%) is similar to levels of resistance in *Avena* spp. within other cropping regions of southern Australia (Walsh, 1995; J. Broster. pers. comm.). In this survey, the maximum seedling survival of a single biotype was 23% (Table 3.4). Given all populations included a substantial 'susceptible' component, growers would most likely achieve reasonable control of *Avena* spp. if an ACCase inhibitor was used the following year. However, continual use of ACCase inhibitors without the integration of alternative methods of control would eventually render this group of herbicides (primarily the APP class) ineffective.

The survey demonstrated that herbicide resistant wild oat populations were located throughout the sampling area (Figure 3.3). This agrees with Mansooji *et al.* (1992) who state that resistance in *Avena* spp. probably develops *in situ* and therefore the extent of resistance in populations varies from field to field. Although there was no difference between the pure *A. fatua* and *A. ludoviciana* populations in their levels of resistance to diclofop-methyl, it is interesting to note that for samples which comprised both species, there was a tendency toward increased resistance (Table 3.6, $P = 0.09$). However, according to Holtum (1992), *A. fatua* and *A. ludoviciana* do not differ in their general patterns of resistance.

It is generally accepted that a higher level of resistance is associated with larger plant populations. However, this study found that the level of wild oat plant infestation within fields was not related to the level of resistance (Table 3.5). Also, all populations in which resistance was determined, contained more than 70% susceptible plants (Table 3.4). The susceptible portion would most likely be killed if an ACCase inhibitor was utilised, therefore lowering plant numbers compared to a biotype which was totally resistant. It is thus likely that the high percentage of susceptible plants (irrespective of resistance) may account for the lack of association between infestation levels of *Avena* spp. and resistance to diclofop-methyl. The continued recruitment of susceptible individuals from the seed bank (slowing the rate of resistance) would also contribute to the susceptible component of an *Avena* spp. population.

3.4.2 Conclusion

The aim of the survey was to determine the incidence of, and extent of herbicide resistance in *Avena* spp. for a major cropping region of southern Australia. The results demonstrated that not only are wild oats a serious and widespread weed of crops in the mid-north of South Australia, but *A. fatua* and *A. ludoviciana* have proliferated in varying proportions. It was also determined that 2.3% of fields contained an agronomically significant level of resistance to the ACCase inhibitor, diclofop-methyl. Furthermore, 27% of the *Avena* spp. populations displayed some resistance to diclofop-methyl, albeit at a low level. The *Avena* spp. seed samples were collected in 1993 and due to the extensive scale of farming in the mid-north of

South Australia and the heavy reliance on ACCase inhibitors for wild oat control, resistance levels would have probably increased.

The prevention and control of herbicide resistant *Avena* spp. requires the utilisation of IWM techniques. The rotation of herbicide groups is an important strategy for this purpose, however, it is essential that cultural measures also be incorporated into an integrated system to help slow the onset of herbicide resistance. The results from the survey indicate that IWM is needed for the sustainable control of wild oats in the mid-north of South Australia, and for other intensive cropping regions of southern Australia where *Avena* spp. are a problem.

Chapter 4

4. The effect of management practice and depth of seed burial on the seed bank decline of *Avena* spp.

4.1 Introduction

Integrated weed management that places a high priority on managing seed banks has potential to help reduce other weed management inputs (Dyer, 1995). Therefore, integral to the development of integrated systems must be a thorough understanding of the population dynamics operating within weed seed banks. Successful control measures can then be implemented that target weeds at appropriate stages of their life cycle. As information on the population dynamics of *Avena* spp. is currently lacking for southern Australia, fundamental data is required if we are to understand the impact of wild oats in farming systems.

The composition and density of weed seed banks usually reflects the long term crop rotation and weed management techniques previously employed (Froud-Williams, 1988). The seed bank can be regarded as a form of 'memory' of past agricultural practices in a field. For *Avena* spp., seed survival in arable land is generally between four and five years, whilst under pasture conditions it is thought to survive a longer period (see 2.2.9.1). This has ramifications for the use of pasture as a successful control technique for wild oats, since residual seeds may allow rapid reinfestation when moving into cropping after a pasture phase (Medd, 1997). Apart from work undertaken by Mansooji (1993), there has been no published research conducted on the longevity of *Avena* spp. seed in the soil under southern Australian conditions.

Seed dormancy is a major survival characteristic of many weeds, including wild oats. Because of dormancy, seeds which germinate in any given season may represent only a small fraction of the total seed bank. In Australia, Quail and Carter (1969) found that different strains of *A. fatua* and *A. ludoviciana*, exposed to the same germinating temperature, displayed variable patterns of dormancy. Seed dormancy is a key process controlling *Avena* spp. recruitment and seed longevity (Medd, 1996a).

Depth of seed burial may also affect seed dormancy of *Avena* spp., therefore influencing seed survival in the soil (see 2.2.9.2). Vertical distribution of seed within the soil profile has important implications for subsequent reinfestation, particularly where minimum tillage is practiced and freshly shed seeds are located at or near the soil surface (Froud-Williams, 1987). Although some glasshouse studies (Quail and Carter, 1968; Paterson *et al.*, 1976a) have been undertaken, there has been no field research in Australia to determine the effect of depth of seed burial on the survival of wild oats.

To understand the population dynamics of weed seed banks it is important to determine the extent and timing of seedling emergence, and the life span of seed in the soil (Peters, 1991). Therefore, studies were undertaken to define the seed bank decline and emergence pattern of several *Avena* spp. populations. Various factors that influence seed bank dynamics were investigated, including management practice and depth of seed burial.

4.2 Materials and Methods

In November 1992, seed from four distinct *Avena* spp. populations were collected from fields where a grain crop was being grown, in the southern region of South Australia (36°19' S, 140°46' E). Two populations were *A. fatua* and two were *A. ludoviciana*. Assessment through dose response studies determined that each species included an ACCase inhibitor susceptible and ACCase inhibitor resistant biotype. For simplicity, the four populations are abbreviated as; SF (susceptible *A. fatua*), RF (resistant *A. fatua*), SL (susceptible *A. ludoviciana*) and RL (resistant *A. ludoviciana*).

During 1993, seed from each population was multiplied at two sites; Roseworthy and Waite (34°58' S, 138°38' E). Seed multiplication was undertaken to provide sufficient seed for studies beginning in 1994. As plants matured, seeds from each population were collected (December 1993) and bulked in their respective population at each site. All seed was allowed to after-ripen at Roseworthy over the summer period at ambient temperatures (under shelter in the field) for three months. Seeds were then randomly selected within populations and counted into lots (the amount dependant on experimental requirements), in preparation for placement in the field.

The decline of each of these *Avena* spp. population samples (as measured by plant emergence), was monitored over three successive years in field studies (experiments 1 and 2) from autumn 1994. As all experiments were carried out on sites free of wild oats and a known number of seeds were distributed over each plot, the measurement of plant emergence was considered a suitable measure of seed longevity. Seed multiplied in 1993 at Roseworthy or Waite were only used for studies at that site (seed multiplication occurred on areas adjacent to the experimental sites). The soil type at Roseworthy was a solonised brown soil (63% sand, 10% silt, 27% clay, pH($CaCl_2$) 7.04), and at Waite, a red-brown earth (18% sand, 63% silt, 19% clay, pH($CaCl_2$) 7.08). At each location, temperature and rainfall data during the growing season were obtained from a weather station near each experimental site. Monthly rainfall data for each site is listed in Appendix 1.

To estimate the seed longevity of *Avena* spp., the seed bank half-life was calculated using the data collected in each study. At both Roseworthy and Waite, there was sufficient rain by 15/5/94 to induce seed germination. Therefore, the number of days from this date, to when 50% of seedlings had emerged (for the three year experimental period) was estimated as the seed bank half-life of germinable wild oats. Supplemental observations of emergence were made in 1997. Thus the actual seed bank half-life calculated for *Avena* spp. in experiment 1 cannot be confirmed as the seed banks were not exhausted.

4.2.1 Experiment 1

Studies were conducted at two sites (Roseworthy and Waite) to determine the effect of management practice on the seed bank decline of *Avena* spp. The experimental design was a RCBD (randomised complete block design) with four *Avena* spp. populations (SF, RF, SL, and RL) x three management practices (bared, cultivated and pasture). It included four replications at Roseworthy and three at Waite. Plot size for the experiment was 1 x 1 m, with a 0.5 m buffer between plots.

Throughout the experimental period, soil was not disturbed on the bared management plots. The cultivated treatment was an annual cultivation (using a three-pronged garden fork to a depth of 7 cm) at the beginning of each growing season (Table 4.1). Cultivation was undertaken at this time to simulate an 'autumn tickle' (early season

cultivation) and to avoid disturbance (and thus a possible seedling kill) at times when large numbers of seedlings may be emerging. The pasture plots had no soil disturbance. All herbage from the pasture plots was cut (using a lawn-mower or hand shears to a height of 3 cm) and the biomass removed to simulate livestock grazing. This was undertaken approximately three to four times each year (in August to October), when plants had reached approximately 15 cm in height.

Table 4.1 Operations undertaken for the cultivated and pasture management plots during experiment 1.

Management practice	Procedure	Date undertaken	
		Roseworthy	Waite
Cultivated	cultivation	8/6/94, 8/5/95, 18/4/96	9/6/94, 6/5/95, 16/4/96
Pasture	pasture topping	27/10/94, 6/11/95, 15/10/96	26/10/94, 30/10/95, 14/10/96

At Roseworthy (21/4/94), 1000 seeds were evenly distributed over each 1 m^2 plot to a depth of 3 cm. This procedure was repeated at Waite (12/5/94), with 500 seeds being sown per plot. During the experimental period, plant emergence (appearance of seedlings above ground) counts of *Avena* spp. were made at approximately monthly intervals during each growing season. After each assessment, seedlings from the bared and cultivated plots were killed using paraquat to prevent seed production. Paraquat (at 200 g a.i./ha) was either applied using a hand-held boom sprayer or painted directly onto seedlings with a brush. In contrast, *Avena* spp. plants from the pasture plots were cut (at the appropriate height) and sprayed with paraquat once - at the end of the growing season (pasture-topping) to prevent seed set (Table 4.1). In addition, post emergence herbicides (MCPA, 2,4-D or Dicamba) were used when necessary at each site to control broadleaf weeds such as *Polygonum aviculare*, *Malva* spp., *Lamium amplexicaule*, *Tribulus terrestris*, *Chenopodium album*, *Emex australis* and *Sisymbrium orientale*.

4.2.2 Experiment 2

An experiment was conducted at Roseworthy to determine the effect of depth of seed burial on the seed bank decline of *Avena* spp. The experimental design was a RCBD

with five replications and at 50 cm intervals, open-ended steel cylinders (25 cm diameter) were buried to a depth of 12 cm (with 2 cm projecting above the surface). On 21/4/94, 250 seeds were sown to each cylinder at one of two depths. The treatments included, four *Avena* spp. populations (SF, RF, SL, and RL) x two depths (2 and 10 cm). Apart from when the cylinders and seed were placed in the ground, all plots had no soil disturbance.

Avena spp. that had emerged were counted at approximately monthly intervals during each growing season, with seedlings being killed after each assessment as in experiment 1 (4.2.1). Likewise, post emergence herbicides were used when necessary to control broadleaf weeds.

4.2.3 Analysis

For experiments 1 and 2, statistical analysis was undertaken using Genstat 5 (Rothamsted Experimental Station, UK) and analysed as an RCBD with a factorial treatment structure. Treatments were compared for seed bank decline at each sampling date. To account for differences in the seed viability of individual wild oat populations, seedling numbers at each date were converted to a percentage of total emergence (over the experimental period) for each treatment.

4.3 Results

4.3.1 Experiment 1 - effect of management practice on the seed bank decline of *Avena* spp.

4.3.1.1 Influence of environment on the emergence of single cohorts of *Avena* spp.

The relationship between emergence of *A. fatua* and *A. ludoviciana* seedlings, and climatic conditions for 1994 to 1996 at Roseworthy and Waite, are shown in Figures 4.1 and 4.2. At both experimental sites, 1994 (year 1) was a 'drought', as rainfall was substantially lower than long term averages, whilst 1995 (year 2) and 1996 (year 3) produced average levels of rainfall (Appendix 1). Emergence of *A. fatua* and *A. ludoviciana* for the three year period occurred throughout each growing season (winter and spring), although at several sampling dates differences were noted between species. In 1994 at Waite, the proportion of *A. fatua* emergence was substantially greater than *A. ludoviciana* throughout June (sampling occurred on 9/6

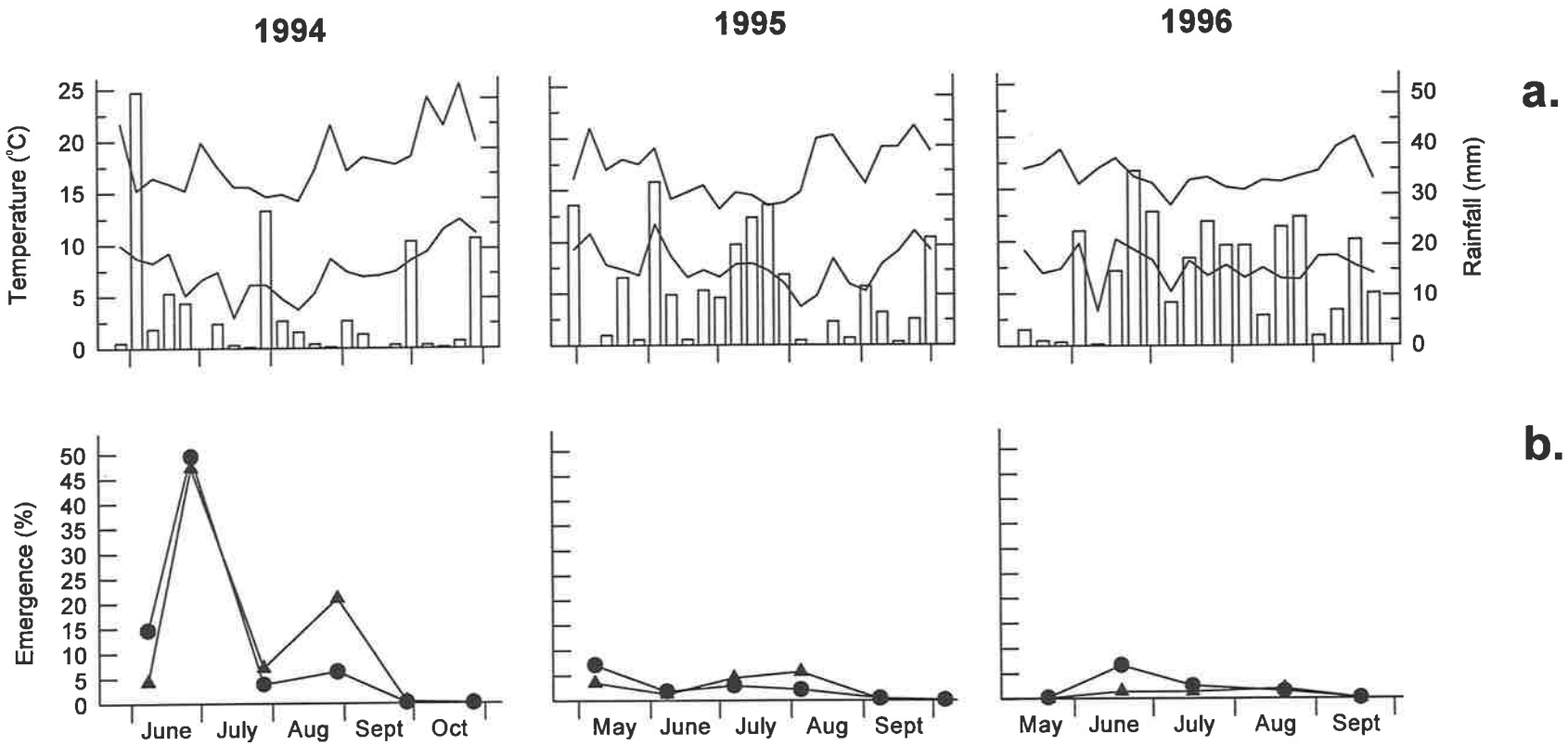


Figure 4.1 (**a**) Average minimum and maximum weekly temperature, and weekly rainfall (columns) at Roseworthy and (**b**) the emergence of a single cohort of *A. fatua* (●) and *A. ludoviciana* (▲) as a percentage of total emergence in experiment 1. Emergence for each *Avena* species is an average of two populations for three management practices.

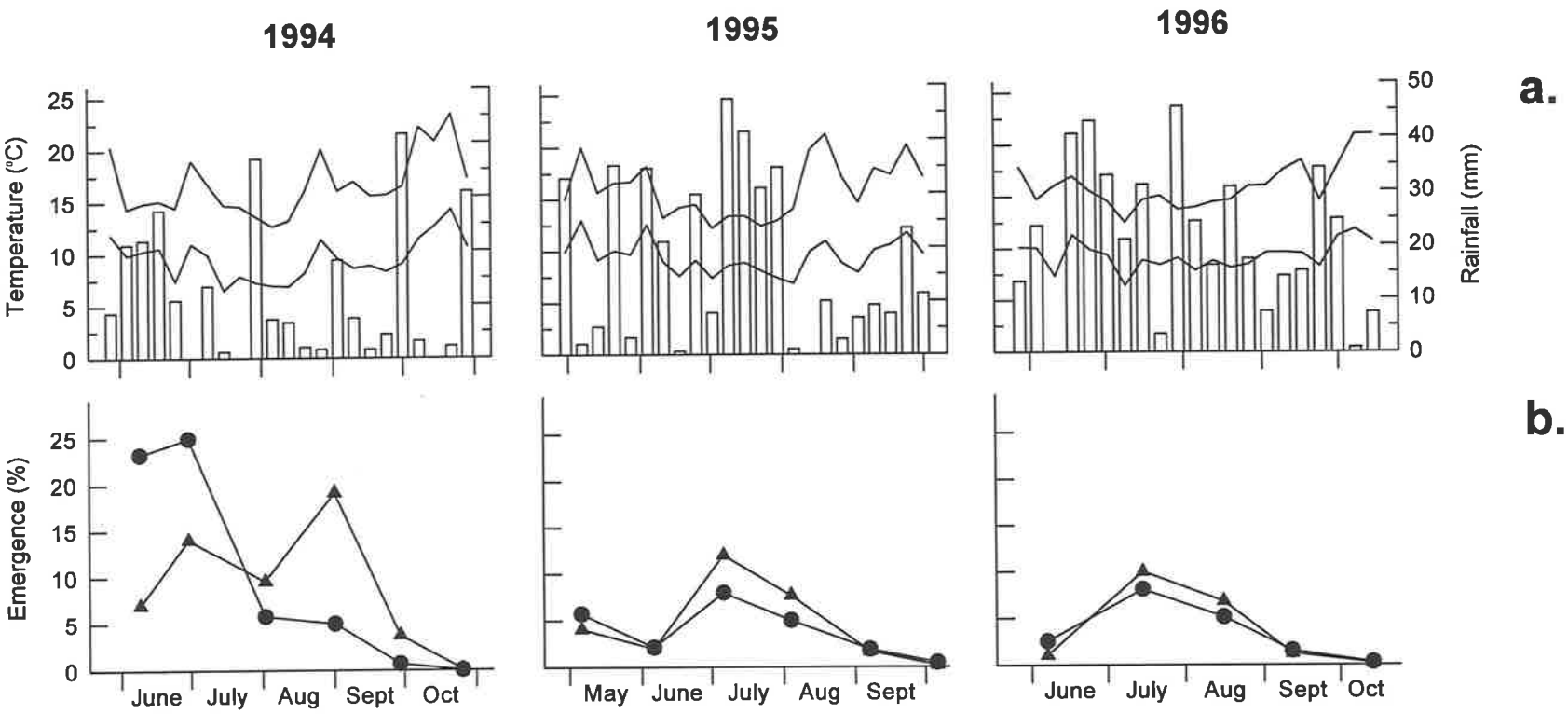


Figure 4.2 (**a**) Average minimum and maximum weekly temperature, and weekly rainfall (columns) at Waite and (**b**) the emergence of a single cohort of *A. fatua* (●) and *A. ludoviciana* (▲) as a percentage of total emergence in experiment 1. Emergence for each *Avena* species is an average of two populations for three management practices.

and 30/6/94), whilst at both sites a greater emergence of *A. ludoviciana* was recorded at the end of August. Similar emergence patterns were recorded for *A. fatua* and *A. ludoviciana* in the final two years at each site (Figures 4.1b and 4.2b).

4.3.1.2 Effect of management practice on the seed bank decline of single cohorts of *Avena* spp.

As seed production was prevented in all treatments, the data shows the pattern of seed bank decline of single cohorts of *Avena* spp. over the three year monitoring period (Tables 4.2 and 4.3). At both sites, greatest emergence occurred in the first growing season. By the end of year 1, 77% and 56% of *Avena* spp. seedlings had emerged (averaged over all treatments) at Roseworthy (Table 4.2) and Waite (Table 4.3) respectively. Significantly less emergence occurred in years 2 and 3 at both sites, although seed bank decline followed the same general pattern as year 1 (Figures 4.3 and 4.4).

When comparing the cumulative decline in emergence between treatments, statistical analysis confirmed several interactions for most sampling dates (Tables 4.2 and 4.3). A species (*A. fatua* or *A. ludoviciana*) x biotype (herbicide susceptible or herbicide resistant) interaction was consistently found at each site. At Roseworthy, RF declined at a significantly greater rate in year 1, whilst later in the year, SL was significantly reduced (relative to SF and RL) (Table 4.2). In contrast, SF generally declined at a faster rate than RF and SL in all years at Waite (Table 4.3). A species x management practice (bared, cultivated or pasture) interaction was also found for most sampling dates at each location (Tables 4.2 and 4.3). At Roseworthy, *A. fatua* (SF and RF) x pasture, and *A. ludoviciana* (SL and RL) x bared and cultivation, consistently declined at a faster rate compared to other, species x management practice combinations (Table 4.2). Similar results were determined at Waite, where *A. fatua* x pasture, and *A. ludoviciana* x cultivation decreased at a greater rate (Table 4.3).

Although interactions were confirmed for most sampling dates at each site, it is worth noting the influence of management practice, *Avena* species and biotype (ie. the main effects) on seed bank decline. The effect of management practice on seed bank decline are illustrated in Figures 4.3 (Roseworthy) and 4.4 (Waite). At Roseworthy, management practice had little affect on emergence over the three year period, except in year 1 where a high proportion of seedlings emerged early in the

Table 4.2 The effect of management practice on the seed bank decline (%) of single cohorts of *Avena* spp. (as measured by plant emergence) over a three year period in experiment 1 at Roseworthy.

	Seed survival (%)															
	1994						1995						1996			
Sampling date	8/6	27/6	28/7	29/8	28/9	27/10	8/5	8/6	7/7	5/8	8/9	6/10	22/5	19/6	16/7	20/8
SF (bared)	89.9	51.6	45.5	30.4	30.1	30.0	19.8	17.9	15.1	13.0	12.7	12.6	12.4	5.1	1.6	0.1
RF (bared)	76.7	33.3	30.5	24.4	24.3	24.3	20.8	19.5	17.4	14.9	14.3	14.3	13.9	4.9	2.3	0.2
SL (bared)	92.8	49.0	45.7	14.9	14.5	14.4	12.7	12.1	8.9	4.7	4.5	4.5	4.4	3.1	1.7	0.1
RL (bared)	97.1	61.8	54.4	23.0	22.4	22.3	18.6	17.3	11.9	4.4	4.3	4.2	4.1	2.8	2.1	0.1
SF (cultivated)	90.8	50.4	42.7	32.3	32.1	32.0	22.7	20.6	15.3	12.8	12.3	12.3	12.1	5.0	1.9	0.1
RF (cultivated)	75.5	39.9	33.9	27.6	27.5	27.5	23.8	21.4	16.9	14.6	14.1	13.9	13.5	4.6	1.9	0.3
SL (cultivated)	94.3	53.9	39.5	16.4	15.9	15.7	12.9	12.3	9.3	6.3	6.1	6.1	5.9	4.2	2.6	0.0
RL (cultivated)	97.4	64.2	48.5	21.1	20.6	20.5	17.5	16.7	12.7	5.1	4.9	4.8	4.8	3.6	2.4	0.0
SF (pasture)	92.9	19.8	19.8	19.8	19.8	19.8	9.6	8.0	6.7	5.5	5.5	5.5	5.4	2.5	1.1	0.2
RF (pasture)	86.8	20.3	19.8	19.8	19.8	19.8	14.0	12.5	11.0	8.9	8.4	8.4	8.2	3.8	1.3	0.1
SL (pasture)	94.7	23.2	23.2	19.7	19.7	19.7	15.6	13.4	10.9	6.3	6.2	6.2	6.1	4.0	1.9	0.1
RL (pasture)	98.1	39.2	37.7	28.3	28.3	28.3	22.5	20.6	11.9	4.7	4.2	4.2	4.2	3.2	1.8	0.2
Significance level[†]																
species	***	***	***	*	*	*	ns	ns	ns	***	***	***	***	ns	ns	ns
biotype	**	ns	ns	ns	ns	ns	*	*	ns	ns	ns	ns	ns	ns	ns	ns
management	ns	***	***	ns	ns	ns	ns	ns	ns	*	*	*	*	ns	ns	ns
species x biotype	***	***	***	*	*	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
species x manage.	ns	ns	ns	*	*	*	**	**	*	*	*	*	*	ns	ns	ns

The populations are noted as; SF (susceptible *A. fatua*), RF (resistant *A. fatua*), SL (susceptible *A. ludoviciana*) and RL (resistant *A. ludoviciana*).
[†] * = $P<0.05$, ** = $P<0.01$, *** = $P<0.001$, ns = not significant ($P>0.05$). Statistical analysis determined there was no; biotype x management and no species x biotype x management interaction at any sampling date.

Table 4.3 The effect of management practice on the seed bank decline (%) of single cohorts of *Avena* spp. (as measured by plant emergence) over a three year period in experiment 1 at Waite.

	Seed survival (%)															
	1994						1995						1996			
Sampling date	9/6	30/6	2/8	1/9	29/9	26/10	6/5	6/6	6/7	4/8	7/9	6/10	7/6	15/7	16/8	12/9
SF (bared)	68.3	46.9	40.7	32.3	31.3	31.3	26.8	25.6	18.3	16.4	15.0	14.4	12.9	4.6	1.2	0.4
RF (bared)	81.6	59.6	55.4	49.4	48.3	48.3	43.1	41.4	33.2	27.7	25.0	24.5	21.8	9.9	1.2	0.0
SL (bared)	93.9	80.4	74.8	48.0	43.2	43.0	41.4	40.5	34.4	22.9	21.8	21.8	21.4	10.6	1.5	0.3
RL (bared)	95.6	85.6	79.6	52.5	46.3	46.2	44.0	42.3	34.9	28.5	25.4	24.8	23.8	13.1	1.0	0.2
SF (cultivated)	75.6	49.5	37.7	29.3	28.3	28.3	22.9	19.5	15.1	11.1	9.7	9.7	6.7	4.0	1.1	0.6
RF (cultivated)	88.2	68.6	58.4	51.5	50.5	50.5	44.8	39.3	28.0	21.4	18.3	18.1	15.1	7.5	1.2	0.5
SL (cultivated)	92.6	79.8	55.0	29.2	24.3	24.3	19.6	17.0	11.6	8.7	7.7	7.7	7.0	2.7	0.7	0.1
RL (cultivated)	95.7	83.1	64.6	31.0	24.8	24.6	22.3	20.0	13.7	8.5	7.4	7.2	5.8	3.2	0.6	0.5
SF (pasture)	65.8	34.8	33.8	33.8	33.8	33.8	25.6	24.8	18.8	14.5	13.5	13.2	11.0	5.0	2.0	0.0
RF (pasture)	81.1	51.8	50.6	50.6	50.6	50.6	45.5	45.5	35.0	27.4	26.0	25.0	22.1	10.3	3.7	0.0
SL (pasture)	90.9	74.0	71.8	70.9	70.9	70.9	62.9	61.6	44.1	33.5	33.0	33.0	30.3	12.6	2.3	0.0
RL (pasture)	89.5	71.3	71.1	70.7	70.7	70.7	65.2	62.0	32.9	23.7	20.8	20.8	20.5	6.9	2.3	0.1
Significance level[†]																
species	***	***	***	**	*	*	**	**	ns	ns	ns	ns	*	ns	ns	ns
biotype	**	**	***	***	***	***	***	***	*	*	*	ns	*	ns	ns	ns
management	ns	**	*	***	***	***	***	***	***	***	***	***	***	**	ns	*
species x biotype	**	**	*	**	**	**	**	**	***	**	**	**	***	*	ns	ns
species x manage.	ns	ns	*	***	***	***	***	***	**	*	*	**	**	ns	ns	ns

The populations are noted as; SF (susceptible *A. fatua*), RF (resistant *A. fatua*), SL (susceptible *A. ludoviciana*) and RL (resistant *A. ludoviciana*).
[†]* = $P<0.05$, ** = $P<0.01$, *** = $P<0.001$, ns = not significant ($P>0.05$). Statistical analysis determined there was no; biotype x management and no species x biotype x management interaction at any sampling date.

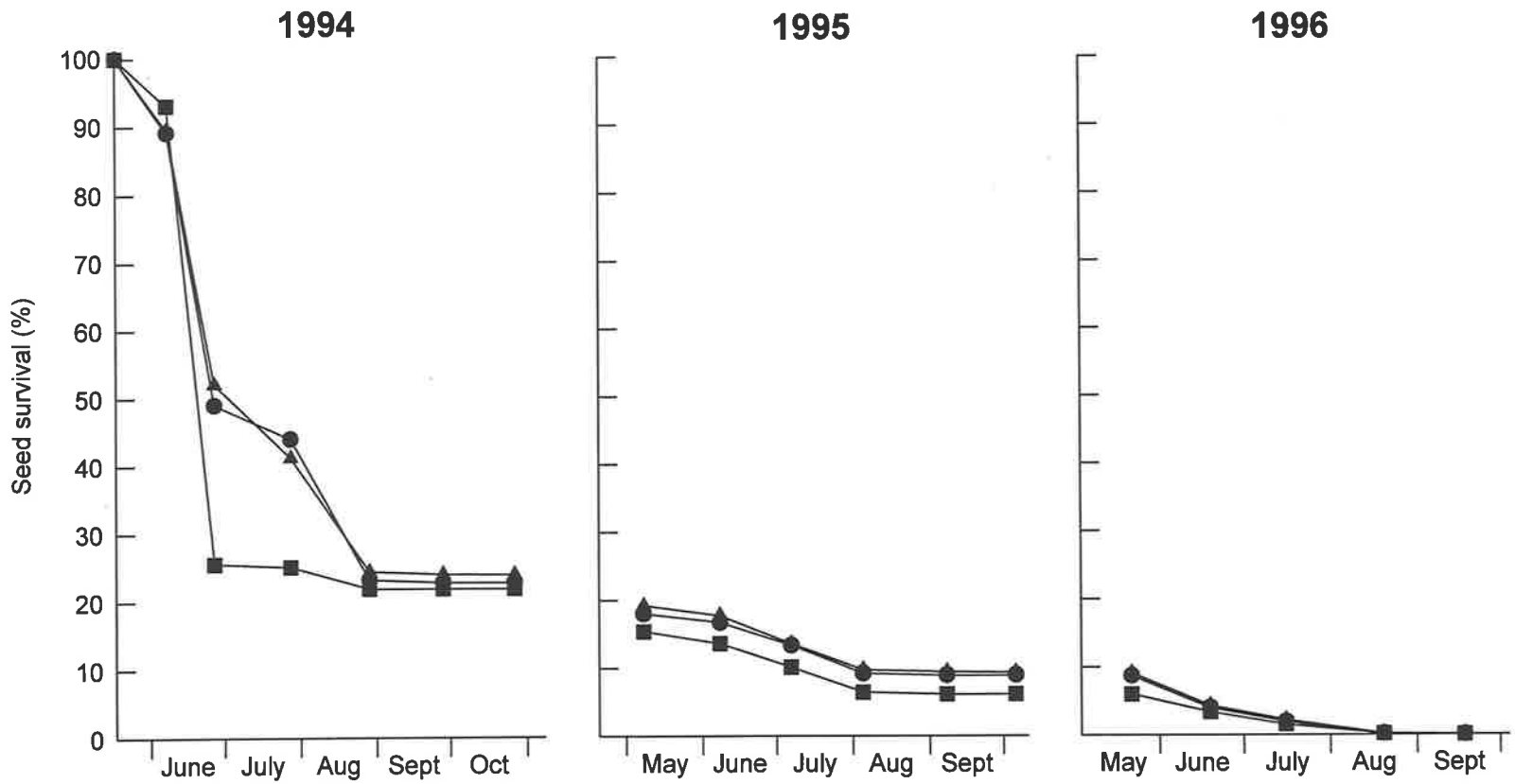


Figure 4.3 The effect of management practice; bared (●), cultivated (▲) and pasture (■) on the seed bank decline (%) of a single cohort of *Avena* spp. (as measured by plant emergence) over a three year period in experiment 1 at Roseworthy. Emergence for each management practice is an average of four populations.

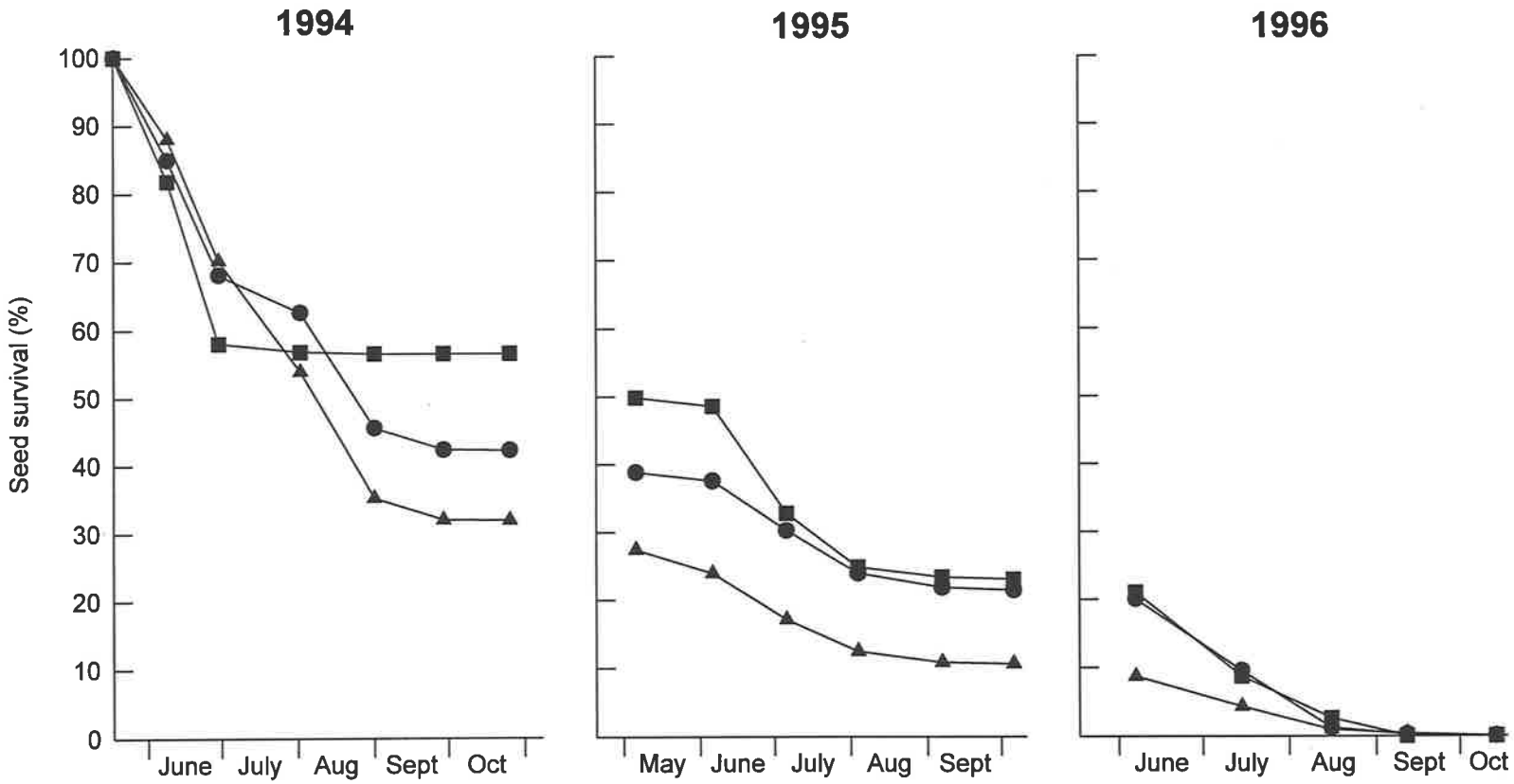


Figure 4.4 The effect of management practice; bared (●), cultivated (▲) and pasture (■) on the seed bank decline (%) of a single cohort of *Avena* spp. (as measured by plant emergence) over a three year period in experiment 1 at Waite. Emergence for each management practice is an average of four populations.

growing season under pasture. At Waite, seed bank decline of *Avena* spp. for the cultivated management practice tended to be faster than the bared and pasture practices. While management practice influenced to varying degrees the rate of decline at each site, actual numbers of seedlings which emerged under pasture were substantially different to the bared and cultivated management practices (Table 4.4). At each site, emergence was reduced by about 25% under pasture, compared with the two other practices.

Table 4.4 The effect of management practice on the total number of *Avena* spp. seedlings (of a single cohort) that emerged over a three year period in experiment 1 at Roseworthy and Waite.

	Total seedling emergence (%)[†]	
	Roseworthy	Waite
Bared	100	99
Cultivated	94	100
Pasture	68	76

[†]Emergence expressed as a percentage of the bared management practice at Roseworthy and the cultivated management practice at Waite. Emergence for each management practice is an average of four populations.

The effect of species and biotype on the seed bank decline of wild oats are illustrated in Figures 4.5 (Roseworthy) and 4.6 (Waite). A comparison of *Avena* species at Roseworthy demonstrated that *A. fatua* declined at a faster rate than *A. ludoviciana* in June and July of year 1, however, from August to October of 1994, and for the same period during year 2, *A. ludoviciana* decline was greater. At Waite, the decline of *A. fatua* was greater than *A. ludoviciana* up until June of year 2, thereafter little change was noted in the decline patterns between the two species. In reference to the effect of *Avena* spp. biotype on seed bank decline, the emergence pattern of the herbicide susceptible populations were similar to that of the resistant populations in all three years at Roseworthy (Figure 4.5). In contrast, the decline of the susceptible populations at Waite were generally greater than for the resistant populations over the majority of the experimental period (Figure 4.6).

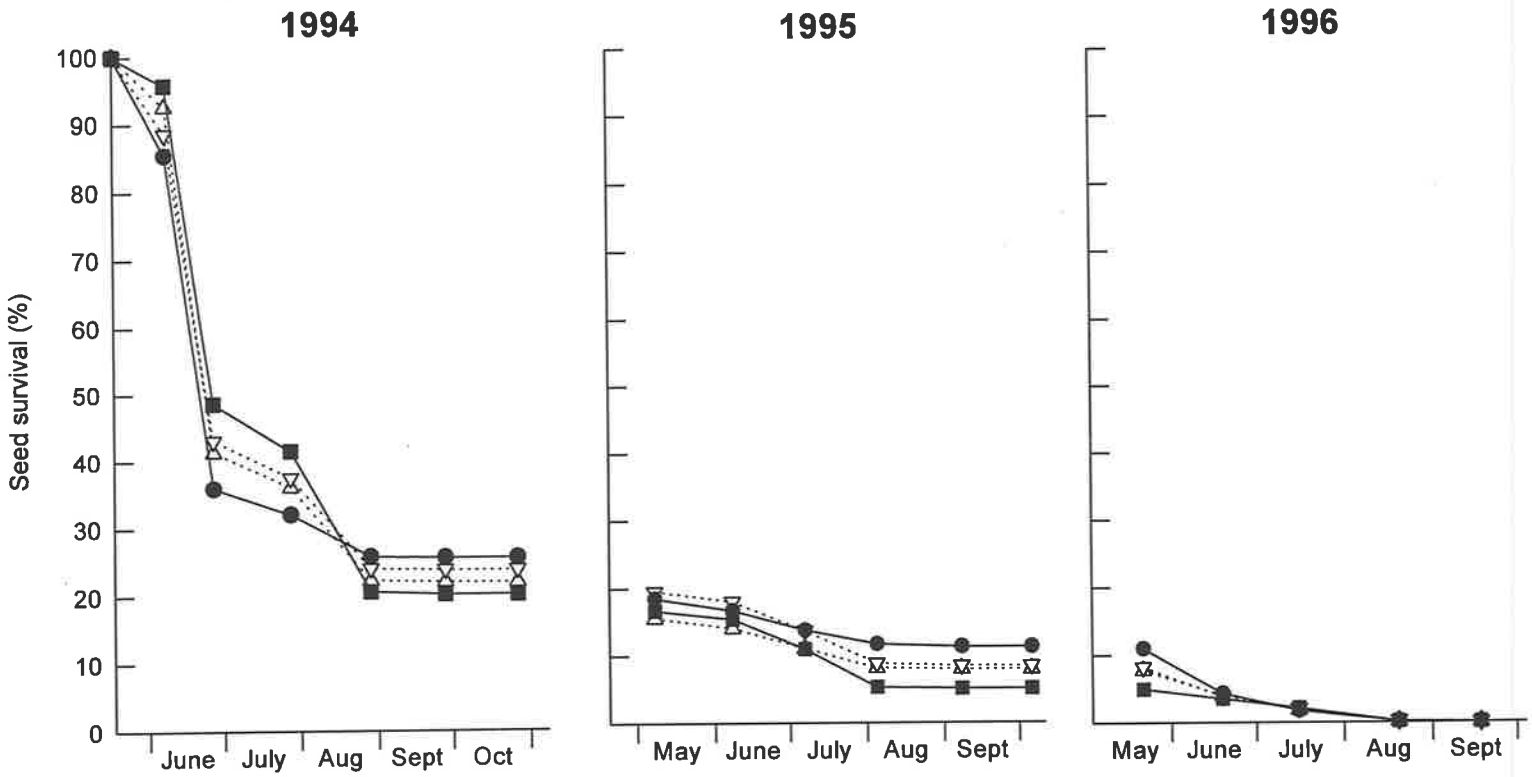


Figure 4.5 The effect of species; *A. fatua* (●) and *A. ludoviciana* (■), and biotype; herbicide susceptible (Δ) and herbicide resistant (∇) on the seed bank decline (%) of a single cohort of *Avena* spp. (as measured by plant emergence) over a three year period in experiment 1 at Roseworthy. Emergence for each *Avena* species and each biotype is an average of two populations for three management practices.

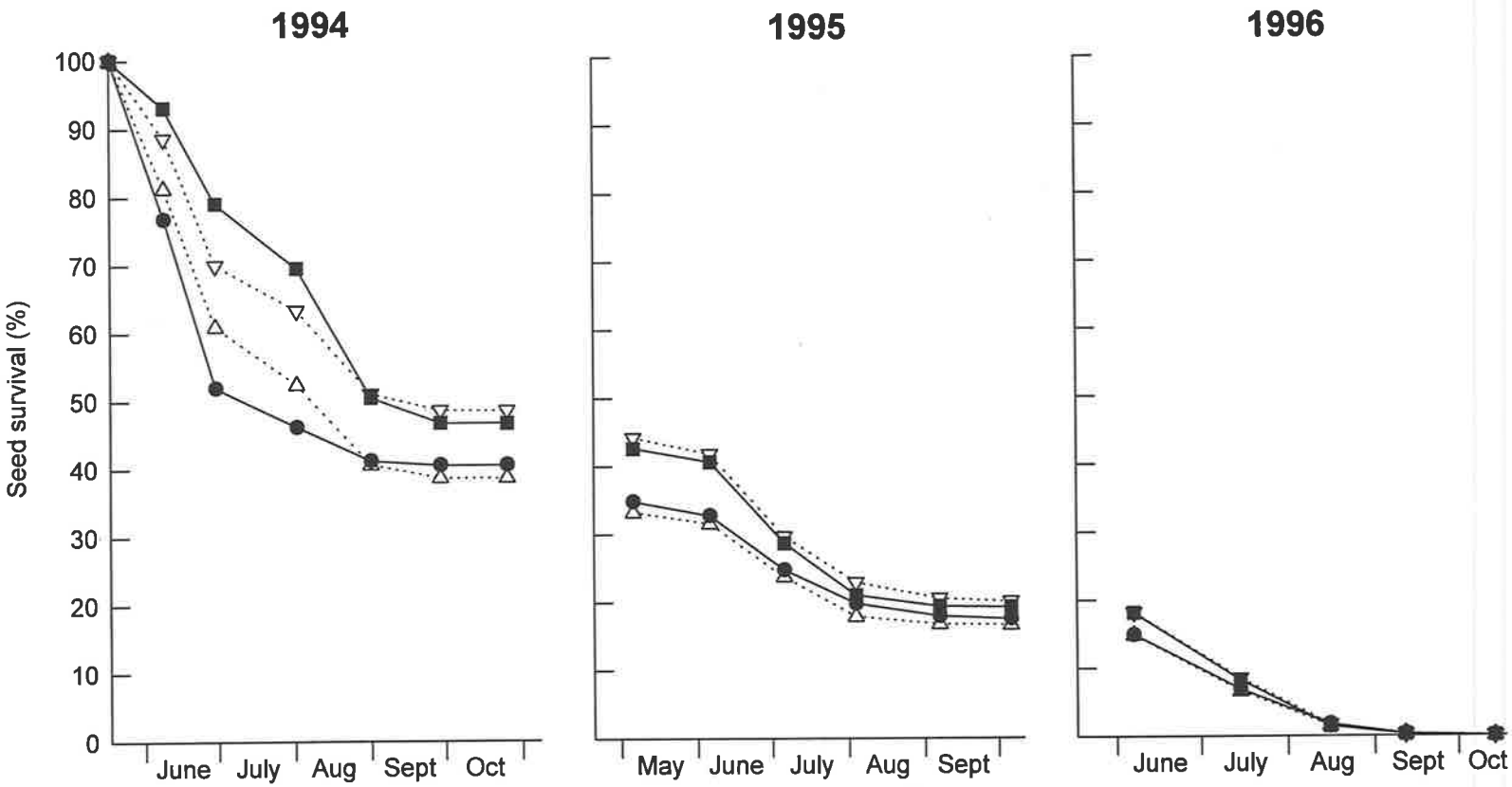


Figure 4.6 The effect of species; *A. fatua* (●) and *A. ludoviciana* (■), and biotype; herbicide susceptible (Δ) and herbicide resistant (∇) on the seed bank decline (%) of a single cohort of *Avena* spp. (as measured by plant emergence) over a three year period in experiment 1 at Waite. Emergence for each *Avena* species and each biotype is an average of two populations for three management practices.

4.3.2 Experiment 2 - effect of depth of seed burial on the seed bank decline of *Avena* spp.

4.3.2.1 Influence of environment on the emergence of single cohorts of *Avena* spp.

The relationship between emergence of *A. fatua* and *A. ludoviciana* seedlings and climatic conditions at Roseworthy in 1994 (year 1), 1995 (year 2) and 1996 (year 3) are shown in Figure 4.7. Emergence of the two species followed similar patterns. Experiment 2 was conducted immediately adjacent to experiment 1 (Roseworthy) using the same ecotypes, and patterns of emergence were similar in each study.

4.3.2.2 Effect of depth of seed burial on the seed bank decline of single cohorts of *Avena* spp.

Like experiment 1, seed production was prevented in all treatments, and so the data shows the pattern of seed bank decline of single cohorts of *Avena* spp. over a three year period (Table 4.5). The greatest emergence occurred in the first year, with 81% of seedlings having emerged by the end of the 1994 growing season (averaged over all treatments). With high rates of emergence in year 1, less than 1% of seedlings emerged in year 3 for seed buried at 10 cm (Table 4.5).

Statistical analysis of the decline in emergence between treatments confirmed a depth of seed burial effect (Table 4.5). *Avena* spp. seed buried at 2 cm initially declined at a faster rate (compared to 10 cm), however, by August of year 1 and for the remainder of the experimental period, the opposite was the case, as the rate of seed bank decline was greater for the 10 cm buried seed (Figure 4.8). Analysis also determined a species x biotype x depth of seed burial interaction for the majority of year 1, where the seed bank of RF (buried at 10 cm) declined at a faster rate, relative to all other treatments (Table 4.5). In addition, analysis verified that *Avena* species or biotype had little affect on the seed bank decline of wild oats (Table 4.5).

Although the seed bank consistently declined at a faster rate for seed buried at 10 cm (relative to seed at 2 cm), actual numbers of seedlings which emerged from each depth for the same *Avena* spp. population were vastly different (Table 4.6). Averaged over all populations, 55% less seedlings emerged from the 10 cm depth, compared to seedlings from 2 cm.

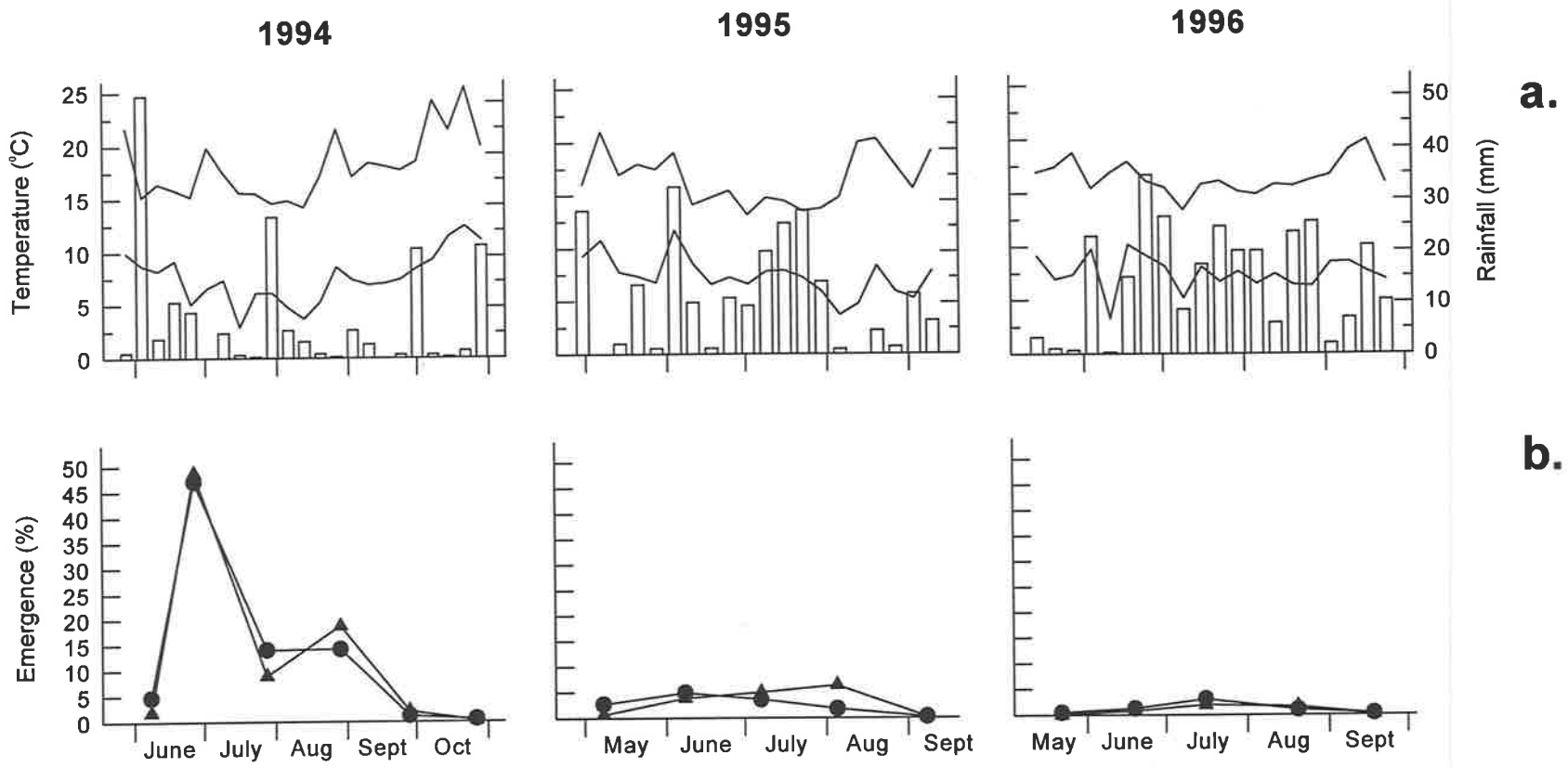


Figure 4.7 **(a)** Average minimum and maximum weekly temperature, and weekly rainfall (columns) at Roseworthy and **(b)** the emergence of a single cohort of *A. fatua* (●) and *A. ludoviciana* (▲) as a percentage of total emergence in experiment 2. Emergence for each *Avena* species is an average of two populations for three management practices.

Table 4.5 The effect of depth of seed burial on the seed bank decline (%) of single cohorts of *Avena* spp. (as measured by plant emergence) over a three year period in experiment 2 at Roseworthy.

	Seed survival (%)														
	1994						1995					1996			
Sampling date	8/6	27/6	28/7	29/8	28/9	27/10	8/5	8/6	7/7	5/8	8/9	22/5	19/6	16/7	20/8
SF (2 cm)	95.2	38.3	35.6	23.0	22.7	22.5	19.3	17.6	14.2	10.1	10.1	9.6	7.0	2.6	0.4
RF (2 cm)	86.6	38.9	33.1	24.0	23.4	23.0	18.1	16.1	13.6	12.7	12.1	11.2	9.2	2.3	0.6
SL (2 cm)	97.6	47.3	45.3	30.9	29.2	29.0	28.0	26.6	20.0	10.7	10.5	10.4	9.4	4.8	0.1
RL (2 cm)	95.5	49.9	45.6	19.4	18.0	17.7	16.8	16.4	13.2	6.0	6.0	6.0	4.5	1.7	0.2
SF (10 cm)	100.0	63.8	45.3	23.3	21.3	20.1	18.5	7.3	2.6	0.7	0.7	0.4	0.4	0.0	0.0
RF (10 cm)	99.4	52.2	23.4	10.5	9.2	9.2	8.2	3.8	0.4	0.4	0.4	0.4	0.4	0.0	0.0
SL (10 cm)	100.0	49.8	34.3	16.3	13.1	13.1	12.6	7.8	3.8	0.7	0.5	0.5	0.0	0.0	0.0
RL (10 cm)	99.8	51.3	37.8	21.8	20.2	20.0	20.0	11.4	5.7	0.2	0.2	0.2	0.2	0.0	0.0
Significance level[†]															
species	ns	ns	*	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns
biotype	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns
depth	***	**	ns	*	**	**	*	***	***	***	***	***	***	***	*
species x biotype	ns	ns	**	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns
species x depth	ns	**	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
biotype x depth	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns
spcs. x btype. x depth	ns	ns	*	**	**	**	**	ns	ns	ns	ns	ns	*	ns	ns

The populations are noted as; SF (susceptible *A. fatua*), RF (resistant *A. fatua*), SL (susceptible *A. ludoviciana*) and RL (resistant *A. ludoviciana*).
[†] * = $P<0.05$, ** = $P<0.01$, *** = $P<0.001$, ns = not significant ($P>0.05$).

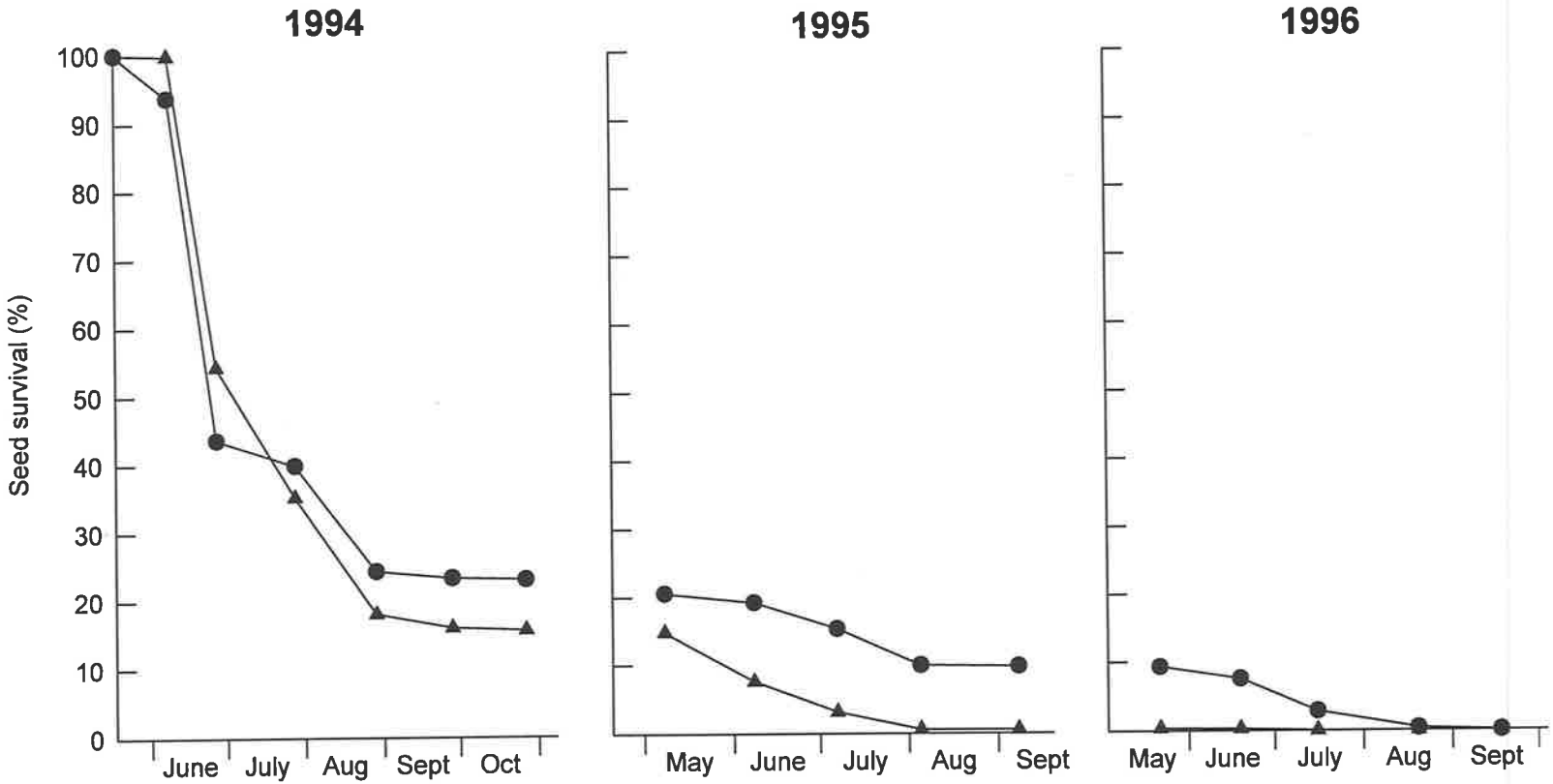


Figure 4.8 The effect of depth of seed burial; 2 cm (●) and 10 cm (▲) on the seed bank decline (%) of a single cohort of *Avena* spp. (as measured by plant emergence) over a three year period in experiment 2 at Roseworthy. Emergence for each depth of seed burial is an average of four populations.

Table 4.6 The effect of depth of seed burial on the total number of *Avena* spp. seedlings (of a single cohort) that emerged over a three year period in experiment 1 at Roseworthy.

	Total seedling emergence (%)†	Rank
SF (2 cm)	69	3
SF (10 cm)	23	7
RF (2 cm)	45	5
RF (10 cm)	21	8
SL (2 cm)	100	1
SL (10 cm)	42	6
RL (2 cm)	84	2
RL (10 cm)	49	4

The populations are noted as; SF (susceptible *A. fatua*), RF (resistant *A. fatua*), SL (susceptible *A. ludoviciana*) and RL (resistant *A. ludoviciana*).
†Treatments expressed as a percentage of SL (2 cm).

4.4 Discussion

4.4.1 Seed bank decline of single cohorts of *Avena* spp.

The decline of single cohorts of four *Avena* spp. populations, established in autumn 1994 and with no further recruitment, was determined for three successive years in field studies conducted at two sites. The studies examined, the influence of management practice (experiment 1) and depth of seed burial (experiment 2) on the decline of wild oat populations. In all studies, seed bank decline (as measured by seedling emergence) generally followed an exponential pattern over the three years, with rates of decline differing between years (Figures 4.3, 4.4 and 4.8). The results indicate that irrespective of site, *Avena* species, biotype, management practice or depth of seed burial, decline generally followed a similar pattern, with by far the greatest emergence of seedlings occurring in year 1. For the two studies conducted at Roseworthy, 77 and 81% of seedlings emerged in year 1 (relative to the total for the three years) (Tables 4.2 and 4.5), whilst 56% of seedlings emerged over the same period at Waite (Table 4.3). With these high initial losses, particularly at Roseworthy, emergence was dramatically reduced in the following years. These results are in agreement with work conducted in a Mediterranean environment by

Sanchez del Arco *et al.* (1995), who found that seed bank decline of *A. ludoviciana* followed an exponential pattern on a yearly basis, with the greatest loss occurring in the first year (57-90%).

In experiment 1, different rates of seed bank decline were measured at Roseworthy and Waite, however, it is difficult to directly compare results between sites even though the same *Avena* spp. seed populations (SF, RF, SL, RL) were evaluated. In the year prior to the studies beginning (1993), populations were multiplied at Roseworthy and Waite, and seed produced at each site was utilised only for studies at that site. Seed produced at each site was therefore subjected to different climatic conditions in 1993 and throughout the experimental period (Figures 4.1a and 4.2a). Environmental factors have a large influence on wild oat seed dormancy (Simpson, 1992) and possibly caused a variation in the proportion of dormant seeds between sites (Peters, 1991). Since seed dormancy is a key process controlling seedling recruitment and seed longevity, differing decline rates for each site were not unexpected. According to Sanchez del Arco *et al.* (1995), the persistence of wild oat seeds buried in the soil can vary with seed source and environmental conditions of the site.

In 1997, sporadic emergence of *Avena* spp. seedlings was noted in all studies and for all treatments, except for plots where seed was buried at 10 cm (experiment 2). During 1997, emergence was not measured at regular intervals (like 1994-96), however, it is estimated that total emergence for the year was approximately 30% of that recorded in 1996 (an assessment from all studies for treatments where emergence occurred). Given the continuing emergence of seedlings throughout 1997, the actual length of *Avena* spp. seed survival cannot be confirmed. However, the rapid decline in wild oat emergence during year 1 suggests the seed bank life of *Avena* spp. in these studies is relatively short. An estimate of seed bank half-life (an indicator of actual seed longevity) for wild oats may be derived from the data in experiment 1 ((Table 4.2 and Figure 4.3 (Roseworthy), Table 4.3 and Figure 4.4 (Waite)). Despite treatment differences, the results from experiment 1 suggest the average seed bank half-life of *Avena* spp. was approximately 40 days at Roseworthy and 100 days at Waite. While these estimates assume seed banks were exhausted after three years, the actual half-life values would most likely increase little given the high proportion of

seedling emergence in the first year. Even allowing for the fact that emergence may continue for several years, the continued rate of decline after year 1 suggests future emergence would be small and therefore have minimal affect on the predicted half-life values.

Previous work in northern New South Wales (Martin and Felton, 1993) reports the seed bank half-life of a mixed *A. fatua* and *A. ludoviciana* population to be about 180 days, a greater length than reported here. Apart from environmental conditions during the growth of *Avena* spp. plants, seed dormancy is also affected by the stage of maturity at which seeds are harvested and the temperature, relative humidity, and light conditions in which seeds are stored after harvest (after-ripening period) (Quail and Carter, 1969). These factors may have acted individually or jointly, resulting in seed samples with low innate, and or induced dormancy, and thus possibly permitted the high emergence in year 1.

4.4.2 Effect of management practice on the seed bank decline of single cohorts of *Avena* spp.

Management practice (bared, cultivated and pasture) influenced the pattern of seed bank decline of wild oats throughout the three year experimental period at both sites (Roseworthy (Figure 4.3) and Waite (Figure 4.4)) in experiment 1. Since seed bank decline rates are an indicator of seed longevity, these results agree with Sanchez del Arco *et al.* (1995), who report that the level of persistence of *Avena* spp. seeds buried in the soil may vary with cultural practice. In addition, analysis at each sampling date highlighted an *Avena* species x management practice interaction. Interestingly at both sites, seed bank decline occurred at a faster rate for the combinations of *A. fatua* x pasture, and *A. ludoviciana* x cultivation, compared with most other combinations for the majority of the experimental period (Tables 4.2 and 4.3).

Although several *Avena* species x management practice interactions were determined, decline rates for individual practices were generally inconsistent between sites. Differences between Roseworthy and Waite (experiment 1) were not unexpected (discussed in 4.4.1), however, several differences require further discussion. At Waite, the seed bank decline for the cultivated management practice (soil disturbance at the beginning of each growing season) was generally greater

compared to the undisturbed treatments (Figure 4.4). This contrasts with the results at Roseworthy where management practice had no affect on the pattern of seed bank decline, except under pasture at the beginning of year 1 when a rapid emergence of seedlings was noted (Figure 4.3). The findings at Roseworthy disagree with the assumption that cultivation generally increases germination (Chancellor, 1976), which results in a greater decline of seed reserves (Peters, 1991) if seed production is prevented. The number of *Avena* spp. seedlings which had emerged by the end of the experimental period were similar for the cultivated and bared practices at both sites (Table 4.4).

Although the total numbers of seedlings which emerged for the bared and cultivated management practices were similar, the numbers were substantially less at both sites under pasture (Table 4.4). In the UK, Thurston (1966) and Wilson and Phipps (1985) found that pasture seed banks were not depleted to the same extent as for arable situations, due to the lack of soil disturbance. Although cultivation stimulated emergence in year 1 at Waite (Figure 4.4), it did not affect the total amount of seedlings that emerged after three years (compared to the bared practice) (Table 4.4). Therefore, the results suggest that a high plant density (mostly intra-specific, although other weed species infested the pasture plots) may have contributed to the low number of wild oat seedlings which were observed to emerge under pasture. Given that *Avena* spp. plants were not killed at regular intervals during the growing season on the pasture plots (unlike bared and cultivated), the high density sward created a highly competitive environment. Competition was probably greatest in year 1, since the largest emergence occurred in 1994. In addition, heavy competition in part probably contributed to the low seedling emergence under pasture from July to October 1994 at both sites (Figures 4.3 and 4.4).

4.4.3 Effect of depth of seed burial on the seed bank decline of single cohorts of *Avena* spp.

Experiment 2 was undertaken to determine the impact of depth of seed burial (2 and 10 cm) on the seed bank decline (as measured by seedling emergence) of wild oats over a three year period. It was found that seed buried at 2 cm initially declined at a faster rate. However, from August of year 1 (1994), until the end of the experimental period, the rate of decline was greater for seed buried at 10 cm (compared to 2 cm)

(Table 4.5 and Figure 4.8). In fact by July of year 3 (1996), seedling emergence had ceased for all *Avena* spp. populations buried at 10 cm, whilst emergence continued during 1996 for seed buried at 2 cm (Table 4.5). Although plots were not measured for emergence in 1997, this trend continued (B. Nietschke unpubl.) as emergence was noted for all populations where seed was buried at 2 cm, while no seedlings emerged from 10 cm (of any population).

The results from experiment 2 suggest seed banks were exhausted for all treatments buried at 10 cm. To substantiate this hypothesis, three replicates of the population SF (susceptible *A. fatua*) were exhumed from each depth (on 24/9/97). The soil samples were sieved and seeds found were subjected to the 'pinch test' (Appendix 2) to verify viability. At the 2 cm depth; three, six and eight seeds were recovered for each replicate respectively, whilst at the 10 cm depth no seeds were found (for any replicates). Although the other populations (RF, SL and RL) were not exhumed, the results would most likely be similar.

The findings from experiment 2 indicate that deeper buried wild oat seed are less persistent, however, these results are contrary to research elsewhere. The literature indicates that the depth of seed burial either has; little influence on the persistence of *Avena* spp. seeds (Quail and Carter, 1968; Sanchez del Arco *et al.*, 1995) or, causes increased persistence with greater depth (Banting, 1966; Miller and Nalewaja, 1990). There are no known studies apart from Paterson *et al.* (1976a) that have demonstrated seed persistence is greater near the soil surface. Paterson *et al.* (1976a) working with a sandy loam soil, found that after three years, less than 3% of *A. fatua* seeds buried from 2.5 to 17.5 cm survived burial. In contrast, 9% of seed buried at 0.5 cm remained viable after the three year period. Paterson *et al.* (1976a) suggested that the seed buried at 0.5 cm had a higher survival rate because the surface soil dried out rapidly each time it rained, which contributed to the reduced seed germination. This may also explain why seed survival was greater at 2 cm compared to at 10 cm in experiment 2.

Although the seed bank declined at a faster rate for seeds buried at 10 cm, significantly more seedlings emerged from the 2 cm depth (Table 4.6). Murdoch (1983) working with *A. fatua*, and Sanchez del Arco *et al.* (1995) with *A.*

ludoviciana, have also shown that seedling emergence decreases with soil depth. These studies determined that similar numbers of seed germinated over a range of depths (from 2.5 to 25 cm), with 'lethal germination' (germination without emergence) increasing with greater soil depth. Most likely this was the case in experiment 2, where a larger proportion of seeds buried at 10 cm suffered 'lethal germination', compared to seeds at 2 cm. This perhaps indicated a particular pattern of soil moisture penetration that may have been a feature of the soils in this work.

If the results from experiment 2 were applied to agronomic management, wild oat seeds should be buried deeply to reduce seed persistence (ie. increase seed bank decline) and seedling emergence. This could be achieved through inversion of the soil using a disc plough. However, given the recognised benefits of minimum (non-inversion) tillage (which leave most weed seed near the soil surface) and the prohibitive cost of ploughing, this technique is impractical for the management of *Avena* spp. in southern Australia (Medd, 1996b). In any case, experiment 2 should be repeated at various sites and include a wider range of depths to substantiate the findings. This is especially pertinent since the vast majority of research indicates *Avena* spp. seed banks do not decline faster with increased soil depth.

4.4.4 Effect of *Avena* species and biotype on the seed bank decline of single cohorts of *Avena* spp.

The effect of *Avena* species (*A. fatua* and *A. ludoviciana*) on seed bank decline was variable between studies. In all studies, neither species consistently declined at a greater rate for the majority of the experimental period, although at Waite (experiment 1) the decline of *A. fatua* was faster until July of year 2 (Figure 4.6). In experiment 1 at Roseworthy, *A. fatua* and *A. ludoviciana* varied in their rates of decline at various stages throughout the experimental period, however, *A. fatua* declined at a faster rate until July of year 1 (Figure 4.5). In contrast, species virtually had no affect on seed bank decline over the three years in experiment 2 (Table 4.5). Despite the variability in these results, the findings agree with Sanchez del Arco *et al.* (1995) who indicated that no firm evidence has been collected to suggest that the seed longevity of *A. fatua* and *A. ludoviciana* are different.

The pattern of seedling emergence dictates the rate of seed bank decline, and in each study similar patterns in emergence were generally noted between *A. fatua* and *A. ludoviciana*, particularly in years 2 and 3 (Figures 4.1b, 4.2b and 4.7b). However, as discussed above, differences were observed at Waitc. Previous work has found that *A. fatua* and *A. ludoviciana* can produce both similar (Aibar *et al.*, 1991) and variable (Quail and Carter, 1968) patterns of emergence.

Irrespective of species, emergence of wild oats occurred from the end of autumn (May) until mid spring (October) for the three year experimental period in all studies (Figures 4.1b, 4.2b and 4.7b). This extended pattern of emergence is characteristic of *Avena* spp. and illustrates the difficulty of weed management techniques such as delayed seeding and the early application of avenacides to successfully control wild oat seed production in southern Australia. Wild oats did not emerge in summer, since germination is inhibited due to high temperatures and insufficient moisture (Quail and Carter, 1968).

Throughout the growing season, variable patterns of *Avena* spp. emergence were noted for the studies at Roseworthy (Figures 4.1b and 4.7b), compared to experiment 1 at Waite (Figure 4.2b). This may in part be explained by the differences in climatic conditions throughout the experimental period at each site (Figures 4.1a and 4.2a). Both soil moisture (Paterson *et al.*, 1976a; Fernandez-Quintanilla *et al.*, 1986) and soil temperature (Quail and Carter, 1968; Fernandez-Quintanilla *et al.*, 1990) are critical for germination in wild oats. Therefore, these factors, along with seed dormancy most likely influenced the different patterns of emergence at each location.

The wild oat populations evaluated in experiment 1 and 2 were also classified according to biotype (herbicide susceptible or herbicide resistant). Like species, the influence of biotype on seed bank decline was inconsistent between studies. The studies at Roseworthy found that biotype had no affect on seed bank decline (Table 4.5 and Figure 4.5), while at Waite, the susceptible populations (SF and SL) declined at a greater rate compared to the resistant populations (RF and RL) until year 3 (Figure 4.6). Analysis also highlighted several *Avena* species x biotype interactions at several sampling dates for the experiment 1 sites (Tables 4.2 and 4.3). However, there was no consistent trend in regards to decline rate of populations between

studies. Therefore from these results, it would appear that in terms of the survival of each biotype, there is little difference in their rate of emergence.

Given the variability across studies in the rate of decline between species, and between biotypes, it is hard to predict the effect control mcasures may have on the individual decline rate of *A. fatua*, *A. ludoviciana*, herbicide susceptible or herbicide resistant wild oat populations. This is especially given that only four populations were evaluated and *Avena* spp. are noted for their complex patterns of variation in emergence, both between and within populations (Marshall and Jain, 1970). Also these studies measured the decline rate of single cohorts of wild oats, where as in the field many cohorts are available for recruitment. This may change the pattern of decline from that reported here.

Although, it is most likely *Avena* spp. (irrespective of species or biotype) would react similarly to weed management practices, different decline rates will affect population densities. For example, if *A. fatua* declined at a greater rate compared to *A. ludoviciana* early in the growing season (as reported in two studies), a greater proportion of *A. fatua* would be controlled by a single herbicide treatment if applied at this time. In contrast, control of *A. ludoviciana* grown under similar conditions would be achieved only if the herbicide was applied later in the season. A similar argument could be used if seed bank decline rates differed between biotypes (as recorded at Waite).

4.4.5 Conclusion

This chapter described the seed bank decline of single cohorts of four *Avena* spp. populations over a three year period. Several studies were undertaken at two sites, and determined the effect of management practice (experiment 1) and depth of seed burial (experiment 2) on the decline of populations representing different species (*A. fatua* and *A. ludoviciana*) and biotypes (ACCase inhibitor susceptible and ACCase inhibitor resistant). Despite treatment differences, the results demonstrated that decline followed an exponential pattern, with the greatest loss occurring in the first year (56-81%). This translated into seed bank half-lives of about 40 and 100 days for *Avena* spp. at the two sites. The effect of management practice; bared, cultivated and pasture on seed bank decline was inconsistent between sites, although substantially

less wild oats emerged under pasture compared to the bared and cultivated plots. While experiment 2 determined that the length of survival of wild oat seeds buried at 2 cm was greater compared to at 10 cm, it was also found that significantly more seedlings emerged from the 2 cm depth, most likely duc to increased 'lethal germination' for seeds buried deeper.

Variable rates of seed bank decline were noted between *Avena* species throughout the experimental period, however, these differences were not consistent across studies. Therefore it is suggested that *A. fatua* and *A. ludoviciana* would decline at a similar rate when subjected to weed management techniques. Like species, the influence of biotype on seed bank decline was inconsistent between studies, and indicates that wild oat populations resistant to ACCase inhibitors could be managed similarly to susceptible populations (apart from herbicide treatment).

Irrespective of *Avena* species or biotype, the high initial rates of seed bank decline reported here indicate that wild oat seed banks may be significantly reduced in a single growing season if further seed production is prevented. Although this may be the case, in all studies some emergence was noted after four years and suggests a small portion of the seed bank can retain long term viability. *Avena* spp. also demonstrated an extended emergence pattern, a characteristic which makes the prevention of in-crop seed production difficult. These factors, along with the early seed shedding habit of wild oats, strong competitiveness and ability to produce large amounts of seed from low plant densities, indicates successful management in farming systems requires an on-going commitment by the farmer. This philosophy agrees with Pandey and Medd (1990), who have illustrated by simulation the advantage of adopting a long term approach to controlling wild oats. Since reproduction is the key to the persistence of *Avena* spp. (Medd, 1996a), integrated strategies that directly control seed production have the greatest potential to minimise seed bank populations.

Chapter 5

5. The effect of burning the residues of cereal crops for control of *Avena* spp.

5.1 Introduction

The period between maturation of one crop and establishment of the next crop is a vital time for weed populations. Large quantities of weed seed are produced which may be shed before harvest, removed at grain harvest or returned to the field, or remain with the standing crop stubble (Cussans *et al.*, 1987). After harvest, any weed seed that remain amongst the crop residue may be destroyed through burning. This practice, known as crop stubble burning, has been documented as a method of control for various grass species, including; *A. myosuroides* (Moss, 1980), *Bromus sterilis* (Froud-Williams, 1983), *Aegilops cylindrica* (Young *et al.*, 1990) and *L. rigidum* (Davidson, 1994). This is also true for *Avena* spp. seed, with studies in Canada (Molberg and Banting, 1973) and the UK (Wilson and Cussans, 1975) showing that *A. fatua* are destroyed on the soil surface by crop stubble burning.

Little work has been undertaken in Australia on the effect of burning crop stubble for the control of *Avena* spp. populations. Recent work by Walsh (1995) in Victoria confirmed that burning kills *Avena* spp. seed on the soil surface. However, in this study, wild oats were spread across the site in summer, leaving less time for wild oat self-burial compared to seed that had shed naturally. Watkins (1970) in Queensland has undertaken the only other published research. However, this work was conducted on a heavy self-mulching clay (an uncharacteristic soil type of southern Australia), and uneven distribution of wild oat seed on the soil surface and comparatively low stubble densities (<1.8 t/ha) minimised the effect of stubble burning.

The extent of seed kill by stubble burning is dependent on several factors, including the position of seeds at burning, and the timing and temperature of the burn. The temperature achieved varies with wind speed, and quantity and moisture content of straw. The distribution of the straw, eg. in windrows, spread or chopped, will also influence temperatures and the proportion of the ground affected (Cussans *et al.*,

1987). Moss (1980) working with *A. myosuroides* and Davidson (1994) with *L. rigidum*, found that the reduction in viable seeds through burning was directly related to the quantity of straw burnt and therefore the temperature and duration of the burn. The effect of burning different quantities of stubble for the control of *Avena* spp. seed has not been documented.

The level of seed kill by stubble burning is also dependent on the position or microsite of the seeds at burning (Cussans, 1982). Cussans (1976) states that freshly shed *Avena* spp. seed is equipped with a self-burial mechanism whereby the awn twists with alternate wetting and drying, driving the seed horizontally across the soil surface. Therefore, seed may be driven below a stone, into a soil crack or buried in loose top soil, potentially protecting it from the effects of burning crop stubble. In southern Australian farming systems the grazing of stubble by livestock (particularly sheep) provides a valuable source of feed during summer and autumn. However, intensive grazing may reduce stubble quantity and trample weed seed into the soil, thus reducing seed kill at burning. This was found to be the case with *L. rigidum* (Davidson, 1994). The effect on *Avena* spp. seeds, of livestock grazing crop stubble prior to burning remains unknown.

The timing of a stubble burn also influences the level of wild oat seed mortality. Seed kill of *Avena* spp. on the soil surface is maximised when crop stubble burning is conducted directly after harvest (Molberg and Banting, 1973; Wilson and Cussans, 1975). However, in southern Australian farming areas, burning cannot be carried out until well after harvest (ie. mid autumn) due to fire restrictions. This ensures *Avena* spp. seeds have an extended time for self-burial and consequently a percentage of seed may escape the burn, especially in cracking type soils.

The effects of management practice on weed seed dormancy and germination are complex (Dyer, 1995). Nevertheless, Dyer (1995) postulates that slight adjustments to agronomic practices, including residue management, may have significant effects on seed population dynamics. Purvis *et al.* (1985) demonstrated that *Avena* spp. growth and seed production was increased by 10 and 42 fold respectively, when in the presence of wheat crop residues (compared to field plots with no-residue). Purvis *et al.* (1985) also found that field pea stubble stimulated wild oat growth and seed

production. According to Purvis (1990), the regulation of *Avena* spp. germination by allello-chemicals from living wheat plants, in combination with the stimulatory effects of wheat crop residues, may confer significant advantages to wild oats in continuous wheat systems. This may cause seed production of wild oats to be selectively stimulated in the second and subsequent years of continuous wheat monoculture (Purvis, 1990). If *Avena* spp. production is increased by decomposing crop residues, there are serious ramifications for wild oat management, given that retention of crop stubble is becoming a more significant part of southern Australian farming systems. It is therefore important to assess the effect of stubble management practice on the seed production of *Avena* spp.

This chapter reports the results of field experiments designed to determine the effect of burning the residues of cereal crops for the control of wild oats. Several factors that may influence the level of control are investigated, including the grazing of livestock prior to burning and the quantity of crop stubble at burning. A study was also undertaken to determine the effect of burning crop stubble on the seed production of *Avena* spp. under a continuous wheat rotation, in comparison with other stubble management practices.

5.2 Materials and methods

5.2.1 Experiment 1

A field experiment was conducted in 1994 at Kapunda (34°21' S, 138°55' E) to determine the effect of barley stubble being grazed prior to burning on the control of *Avena* spp. The study was undertaken in a commercial barley (cv. Schooner) stubble that was naturally infested with *A. fatua* and *A. ludoviciana* seed. The soil type of the experimental site was a red-brown earth. Sheep grazed the site at a stocking rate of six sheep/ha for 88 days preceding the burn, except within cages (0.7 x 0.7 m) which guaranteed no grazing. The treatments included two levels of burning (no burning vs. burning) and two levels of grazing (no grazing vs. grazing). The experiment was structured as a RCBD, with four replications and 15 x 15 m burn plots. Before burning, the quantity of stubble was determined from three (0.09 m^2) quadrats per plot, as were the number of *Avena* spp. seeds located on the soil surface. An industrial vacuum cleaner was used to collect the surface seeds from five (0.09 m^2)

quadrats per plot. On 10/5/94, the sheep were removed from the site and burning carried out. The temperature on the soil surface during the burn was measured using K-type thermocouples connected to a data logger, and the time period over which the temperature exceeded 150°C calculated. This temperature limit was used since Hopkins (1936) found that *A. fatua* seeds require at least 105°C for 15 minutes to prevent germination. Surface seed levels were again measured immediately after the burn, and in the ensuing winter months *Avena* spp. plant emergence was recorded from seven (0.09 m^2) quadrats per plot on 19/6 and 17/7/94.

Avena spp. seed samples collected prior to and following the burn were sieved and sub-sampled, and the seed extracted by hand to determine seed quantity. Seeds were evaluated for germinability and viability using the 'laboratory test' (Appendix 2). Seeds which germinated without the assistance of dehusking, pricking and gibberellic acid application were deemed 'germinable', whilst seeds that germinated with and without assistance were recorded as 'viable'. Seed viability percentages were applied to the pre and post burn seed samples to determine the number of viable seed.

Statistical procedures were undertaken using Genstat 5 and analysis was performed using real or transformed data, depending on the distribution of variance from the mean. Analysis of viable seed numbers before (pre) and after (post) the burn were carried out as a RCBD with sub-samples, treating pre burn as a covariate. The pre- and post burn seed totals were also compared using aggregated no graze and graze data. The stubble quantity at the time of burning was analysed with sub-samples, whilst plot means were compared for the temperature, seed viability percentages and plant emergence measurements.

5.2.2 Experiment 2

A field experiment was conducted in 1995 at Kapunda (red-brown earth soil type) to determine the effect of burning different quantities of stubble for the control of *Avena* spp. The study was undertaken in a commercial barley (cv. Schooner) stubble that was naturally infested with *A. ludoviciana* seed. Sheep grazed the site prior to the stubble burn, but were excluded during the experimental period. Before burning, an area infested with *A. ludoviciana* was split into a RCBD, with four replications, and

four treatments were randomly assigned to plots; including three burn treatments (1x, 2x and 3x existing stubble) and a no burn control (existing stubble). The existing level of stubble (3.16 t/ha) was determined from five (0.09 m^2) quadrats per replicate. This dictated the amount of residue added to the 2 (6.32 t/ha) and 3x (9.48 t/ha) stubble level treatment plots. For these treatments, extra residue was obtained adjacent to the experimental site. Plot size for the burn treatments was 9 x 6 m, and 9 x 4 m for the no burn control. The no burn treatment was a smaller area as seedling emergence was the only data collected from these plots.

Burning was carried out on 20/4/95. Data was collected as per experiment 1 (5.2.1), and included for all burn plots; *A. ludoviciana* seeds located on the soil surface (pre- and post burn), temperature of the burn and its duration. Seed germinability and seed viability percentages were calculated using the 'laboratory test' (Appendix 2), whilst the seed viability percentages were applied to the pre- and post burn seed samples to determine the number of viable seed. After the burn, and at monthly intervals during winter, all plots were measured for emergence of *A. ludoviciana* plants.

Statistical analysis (using Genstat 5) of viable seed numbers and seed viability percentages were carried out as a RCBD, treating pre burn as a covariate. Temperature and plant emergence measurements were analysed using plot means. Multiple comparisons were undertaken using the linear contrasts method.

5.2.3 Experiment 3

A field experiment was conducted from 1993 to 1996 at Roseworthy to determine the effect of burning crop stubble and other residue management practices on *Avena* spp. seed production. The experimental site was on a solonised brown soil. On 1/6/93, a field site free of wild oats was cultivated with a scarifier and a mixture of *A. fatua* and *A. ludoviciana* seeds (from a single population) was sown over the site at approximately 50 seeds/m^2 with a culti-drill. Eleven days later, wheat (cv. Janz) was sown at 80kg/ha over the same area using the culti-drill (Table 5.1). During 1993 (also in 1994 and 1995), *Avena* spp. plants were allowed to produce and shed their seed, and the wheat crop was harvested with a small plot harvester (Table 5.1).

Table 5.1 Management operations undertaken during experiment 3.

Management operation	Date undertaken		
	1993	1994	1995
Pre-seeding glyphosate	-	20/6/94	4/5, 23/5/95
Pre-drilled nitrogen	-	22/6/94 (28 N)	4/5/95 (56 N)
Date of sowing	12/6/93 (18 N, 20 P)†	22/6/94 (18 N, 20 P)	24/5/95 (24 N, 27 P)
Post emergent herbicide‡	7/8/93	4/8/94	19/6/95
Harvest	2/12/93	11/12/94	22/11/95

†Values in parentheses indicates the units (kg/ha) of nitrogen (N) and or phosphorous (P) applied.
‡A mixture of metsulfuron-methyl at 4.2 g a.i./ha, fluoxypyr at 150 g a.i./ha and MCPA at 150 g a.i./ha was applied in 1993, whilst chlorsulfuron was applied at 15 g a.i./ha in 1994 and 1995. Target weeds were *Medicago* spp., *Oxalis pes-caprae*, *Emex australis*, *Gallium tricornutum*, *Sisymbrium orientale* and *L. rigidum*.

In 1994, the experimental site was split into a RCBD with four replications and plots were randomly assigned to one of three stubble management treatments; burn, retained and baled. For the burn plots, stubble was burnt annually (with the aim of reducing viable *Avena* spp. seeds on the soil surface). In contrast, all stubble was conserved on the retained plots, and on the baled plots a significant amount of straw was removed after crop harvest. Plot size for the retained and baled treatments were 22 x 3 m, and 22 x 6 m for the burn treatment. The burn plots were of a larger area to ensure a stubble burn representing typical field conditions was achieved. All treatments remained on the same plots for the duration of the experiment.

As in 1993, wheat was sown (at 80kg/ha) across the site in 1994 and 1995, along with fertiliser in the form of diammonium phosphate, whilst urea was pre-drilled before sowing (Table 5.1). Nitrogen application rates increased throughout the experiment to compensate for no pulse crop being in the rotation. Additional management operations for the site were undertaken during the course of the experiment (Table 5.1).

Management operations specific to the burn and baled treatments were carried out annually (Table 5.2). For the baled plots, a small plot harvester with a straw catcher, cut and collected standing stubble (to a height of 10 cm), whilst loose residue was

raked off the plots with a hand-fork. Care was taken to ensure wild oat seeds were not intentionally removed during the process.

Table 5.2 Management operations undertaken for the burn and baled treatments during experiment 3.

Treatment	Procedure	Date undertaken
Burn	stubble burnt	5/5/94, 13/4/95, 11/4/96
Baled	stubble removed	9/3/94 (1.4 t/ha)†, 28/2/95 (1.1 t/ha), 23/2/96 (1.9 t/ha)

†Values in parentheses indicates the amount of stubble removed from the baled plots.

A variety of data was collected throughout the experimental period. The amount of *Avena* spp. seeds in the soil bank (seed production) was determined from 10-15 (0.01 m^2) cores per plot, taken to a depth of 10 cm. Soil cores were collected on 4/5/94, 11/4/95 and 5/4/96, representing 1993, 1994 and 1995 seed shed respectively. All core samples were sieved and the seed extracted by hand to determine seed production, whilst viable seed was determined by the 'pinch test' (Appendix 2). In addition, all plots were monitored for emergence of *Avena* spp. plants throughout the growing season.

To determine the effect of burning wheat stubble on *Avena* spp. seeds on the soil surface, separate data was collected from the burn plots only. These measurements were undertaken as per experiment 1 (5.2.1) and included; seeds located on the soil surface (pre- and post burn), quantity of stubble at burning, temperature and duration of the burn, and seed germinability and seed viability percentages. The seed viability percentages were applied to the pre- and post burn surface seed samples to determine the number of viable seed.

Statistical analysis (using Genestat 5) was performed using the restricted maximum likelihood method for the amount of *Avena* spp. seed in the soil bank between years, whilst within years, ANOVA was carried out using a RCBD with sub-samples. Analysis of seed numbers on the soil surface after burning was also undertaken as a RCBD with sub-samples, whilst plot means were compared for the temperature and seed viability percentages. A split-plot in time structure was employed for the plant

emergence data. Multiple comparisons were undertaken using the least significant difference method.

5.3 Results

5.3.1 Experiment 1 - effect of burning crop stubble on *Avena* spp. seeds after grazing

The grazing by sheep of barley stubble before burning did not significantly reduce the quantity of crop stubble, or intensity and duration of heat generated, compared to the ungrazed plots (Table 5.3). In addition, the number of seeds on the soil surface before (P>0.05, data not presented) or after the burn were not significantly different (Table 5.3). As a result, the no grazing and grazing treatments were aggregated and the pre- and post burn data compared.

Table 5.3 The effect of burning barley stubble (no grazing vs. grazing) on the survival of *Avena* spp. seeds on the soil surface.

	Viable surface seeds (nos./m^2)	Stubble quantity (t/ha)	Peak temp. (°C)	Temp. duration >150°C (secs.)
No grazing	892†	4.97	191	26
Grazing	1223	4.23	235	31
s.e.d.	242	0.42	74	15
Sig. level	ns	ns	ns	ns

†Indicates 'viable surface seeds' data was transformed (log (x)) prior to ANOVA. Actual data is presented, as the high variability within each treatment meant back-transformed values did not satisfactorily represent their respective actual means.

The burning of crop stubble killed a considerable percentage of the *Avena* spp. seed lying on the soil surface. Apart from reducing actual seed numbers on the soil surface (P<0.05, data not presented), burning significantly reduced seed viability (determined by the ability of seed to germinate after dehusking, pricking and gibberellic acid treatment). Before burning, 95% of the *Avena* spp. seed was viable, however, after burning this was reduced to 68% (Table 5.4). Therefore, the overall effect of stubble burning was to reduce viable *Avena* spp. seeds on the soil surface from 2041 to 1057 seeds/m^2, equivalent to 48% mortality (P<0.01).

Table 5.4 The effect of burning barley stubble on the viability of *Avena* spp. seeds on the soil surface.

	Germinable seed (%)	Viable seed (%)
Pre burn	5	95
Post burn	28	68
s.e.d.	2.4	5.3
Significance level	$P<0.001$	$P<0.001$

Although burning the crop stubble killed 48% of *Avena* spp. seeds on the soil surface, a secondary effect was to relieve seed dormancy in a proportion of the 52% remaining surface seed. Before burning, only 5% of intact *Avena* spp. seeds readily germinated (95% were viable), however, after burning, seed germinability increased to 28% (Table 5.4).

Avena spp. plant emergence counts were recorded throughout the winter following burning. The final emergence assessment undertaken on 17/7/94 indicated that burning increased emergence by 43% on the burn (591 plants/m^2) versus no-burn (339 plants/m^2) areas ($P<0.01$). Grazing by sheep before the burn had no affect on *Avena* spp. plant emergence or *Avena* spp. seed viability compared to the ungrazed treatment ($P>0.05$, data not presented).

5.3.2 Experiment 2 - effect of burning different quantities of crop stubble on *A. ludoviciana* seeds

The burning of barley stubble, irrespective of stubble quantity (3.16, 6.32 or 9.48 t/ha) had no affect on actual seed numbers ($P>0.05$, data not presented), however, viable surface seeds were reduced by at least 80% (Table 5.5).

Table 5.5 The effect of burning different quantities of barley stubble on numbers of *A. ludoviciana* seed on the soil surface.

Stubble quantity (t/ha)	Viable surface seeds (nos./m^2) pre burn	post burn	Mortality of surface seeds (%)
3.16	357	65	82
6.32	203	24	88
9.48	422	9	98

The data in Table 5.5 gives an indication of the effect of burning stubble on *A. ludoviciana* seed numbers on the soil surface. However, due to the high treatment variation amongst seed numbers prior to burning (which affects the post burn outcome), covariate analysis was required to verify differences between the stubble quantity treatments. This confirmed that the quantity of crop stubble at burning had a significant affect on the survival of *A. ludoviciana* seeds on the soil surface (Table 5.6). Additional analysis by linear contrasts demonstrated that the burning of 9.48 t/ha of stubble significantly reduced viable seeds on the surface compared to the two lower density treatments (3.16 and 6.32 t/ha) ($P<0.05$). Conversely, the quantity of stubble had no affect on the intensity or duration of heat generated by the burn (Table 5.6).

Table 5.6 The effect of burning different quantities of barley stubble on the survival of *A. ludoviciana* seeds on the soil surface.

Stubble quantity (t/ha)	Viable surface seeds (nos./m^2)	Peak temp. (°C)	Temp. duration >150°C (secs.)
3.16	2.89† (17)‡	367	29
6.32	2.52 (11)	328	66
9.48	1.51 (4)	308	57
s.e.d.	0.39	43	20
Significance level	$P<0.05$	ns	ns

†Data presented for 'viable surface seeds' is adjusted for the covariate (pre burn).
‡Values in parentheses indicates back-transformed means, the data being transformed (log (x + 1)) prior to ANOVA.

Before burning, 87% of the *A. ludoviciana* seed was viable, however, burning reduced the germinability and viability of wild oats seeds, irrespective of the quantity

of stubble burnt (Table 5.7). Amongst stubble quantity treatments, the amount of residue burnt had a significant affect on the viability of *A. ludoviciana* seed (Table 5.7). Further analysis (linear contrasts), demonstrated that the burning of 6.32 and 9.48 t/ha of stubble significantly reduced seed viability compared to 3.16 t/ha ($P<0.05$). Likewise, the same result ($P<0.05$) was realised when the three stubble quantities were contrasted for seed germinability (Table 5.7).

Table 5.7 The effect of burning different quantities of barley stubble on the viability of *A. ludoviciana* seeds on the soil surface.

Stubble quantity (t/ha)	Germinable seed (%)	Viable seed (%)
3.16	15.3	17.0
6.32	5.4	8.0
9.48	2.8	3.8
s.e.d.	3.5	3.8
Significance level	$P<0.05$	$P<0.05$
Pre burn control	47%[†]	87%

[†]Percentage based on an average of all stubble quantity treatments.

Following stubble burning, plant emergence was monitored during winter, however, burning (irrespective of stubble quantity) had no affect on seedlings numbers compared to the no burn treatment (Table 5.8).

Table 5.8 The effect of burning different quantities of barley stubble on the emergence of *Avena* spp. plants (at 25/7/95), relative to the no burn treatment.

Stubble quantity (t/ha)	*Avena* spp. emergence (plants/m^2)
3.16 (burn)	109
6.32 (burn)	80
9.48 (burn)	72
3.16 (no burn)	77
s.e.d.	24
Significance level	ns

5.3.3 Experiment 3 - effect of stubble management practice on *Avena* spp. seed production

5.3.3.1 Effect of stubble management on *Avena* spp. production

The seed bank of *Avena* spp. was measured annually, and irrespective of stubble management treatment, significantly increased each year ($P<0.001$) (Figure 5.1). Analysis within years determined that by 1995 the seed bank of the burn treatment was lower ($P<0.05$) compared to the retained and baled treatments (Figure 5.1).

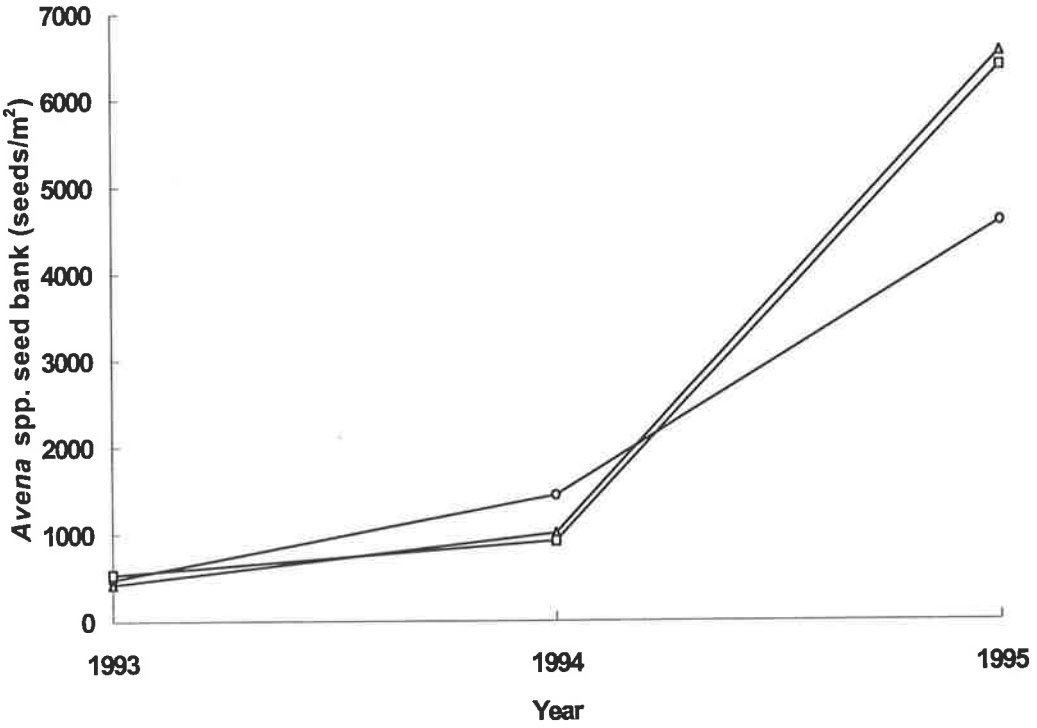


Figure 5.1 The effect of stubble management treatment; burn (O), retained (Δ) and baled (□) on the annual seed bank of *Avena* spp. Back-transformed means are illustrated, the data being transformed (log (x + 1)) prior to analysis and producing a year effect ($P<0.001$), and in 1995 a treatment effect (burn significantly less than retained and baled) ($P<0.05$). (The initial *Avena* spp. seed bank was approximately 50 seeds/m^2).

The emergence of *Avena* spp. plants was monitored throughout each growing season. Analysis identified a treatment x time interaction ($P<0.001$), with plant emergence significantly different between treatments at each date of measurement (Table 5.9).

Table 5.9 Emergence of *Avena* spp. plants throughout the experimental period.

Treatment	*Avena* spp. emergence (plants/m^2)		
	12/8/94	23/7/95‡	12/6/96
Burn	4.69^{a} (108)†	6.77^{b} (875)	6.57^{b} (712)
Retained	5.08^{b} (160)	6.55^{ab} (697)	5.51^{a} (246)
Baled	4.92^{ab} (136)	6.52^{a} (678)	5.46^{a} (236)

Values in columns not followed by the same common letter differ significantly (P<0.05).
†Values in parentheses indicates back-transformed means, the data being transformed (log (x)) prior to ANOVA. Treatment x time interaction s.e.d. = 0.115 for comparison between treatments.
‡Plant emergence counts for 23/7/95 are a cumulative amount for 1995, since some seedlings were killed prior to crop sowing with glyphosate.

5.3.3.2 Effect of burning crop stubble on *Avena* spp. seeds

In 1996, the burning of wheat stubble reduced actual *Avena* spp. seed numbers on the soil surface (P<0.05, data not presented), while viable surface seeds were reduced by 54% (Table 5.10). In 1994 and 1995, stubble burning did not significantly reduce actual (P>0.05, data not presented) or viable surface seed levels (Table 5.10).

Table 5.10 The effect of burning wheat stubble on the numbers of *Avena* spp. seed on the soil surface.

	Viable surface seeds (nos./m^2)		
	1994†	1995†	1996
Pre burn	212 (94-643)‡	646 (160-1824)	5046 (1692-8636)
Post burn	127 (16-538)	345 (129-1130)	2345 (870-4325)
s.e.d.	52	140	534
Significance level	ns	ns	P<0.05
Stubble quantity (t/ha)	2.57	1.55	3.31
Peak temperature (°C)	207	178	230
Temp. duration >150°C (secs.)	23	21	22

†Indicates data was transformed (log (x)) prior to ANOVA for 1994 and 1995. The transformations did not affect the significance level, therefore actual means are presented.
‡Values in parentheses indicates the numerical range associated with each mean.

Burning had a significant affect on the viability of wild oat seeds on the soil surface in all years (Table 5.11). Seed germinability was reduced on average by 22%, whilst seed viability was lowered by 32% (Table 5.11).

Table 5.11 The effect of burning wheat stubble on the viability of *Avena* spp. seeds on the soil surface.

	Germinable seed (%)		Viable seed (%)		
	1995	1996	1994	1995	1996
Pre burn	87	85	98	97	95
Post burn	65	69	57	67	72
s.e.d.	8.4	4.4	13.5	7.8	3.3
Significance level	$P<0.05$	$P<0.05$	$P<0.05$	$P<0.01$	$P<0.001$

Avena spp. seeds were not tested for seed germinability in 1994.

5.4 Discussion

Several field experiments were undertaken to determine the effect of burning the residues of barley and wheat crops on the control of *Avena* spp. These studies (experiments 1-3) demonstrated that viable *Avena* spp. seeds on the soil surface can be reduced through crop stubble burning, with control ranging from 48 to 98%. Furthermore, burning undertaken for consecutive years resulted in a significant reduction in the *Avena* spp. seed bank compared to the no burn treatments (Figure 5.1). These results are in agreement with work from other countries which have shown that seed of *Avena* spp. are destroyed on the soil surface by the burning of crop stubble (Molberg and Banting, 1973; Wilson and Cussans, 1975). In experiment 3, stubble burning undertaken in 1994 and 1995 did not significantly decrease viable wild oat seeds (most likely due to the high variability within treatments), although a downward trend was apparent (Table 5.10). Through affecting viability, the number of viable seeds were consistently reduced after burning. In most cases, burning did not reduce actual *Avena* spp. seed numbers on the soil surface, however, burning always reduced the viability of seeds compared to the viability level before the burn (Tables 5.4, 5.7 and 5.11).

While burning the residues of cereal crops killed wild oat seed on the soil surface, the level of control was variable. This variability in efficacy may be due to several factors, including the timing of the stubble burn, the location of the seed at burning, and the temperature produced by the burn. In turn, the intensity and duration of heat generated is related to wind strength during the burn and, moisture content, distribution and quantity of the stubble.

5.4.1 Effect of stubble quantity on *Avena* spp. seeds at stubble burning

Of the three experiments conducted, the greatest *Avena* spp. seed kill on the soil surface (98%) resulted when 9.48 t/ha of stubble was burnt (Table 5.5). In this study (experiment 2), the quantity of stubble influenced the level of *A. ludoviciana* seed kill, with the burning of 9.48 t/ha of stubble significantly reducing viable surface seeds compared to 3.16 and 6.32 t/ha (Table 5.6). This agrees with work conducted by Davidson (1994) who found a significantly greater mortality of *L. rigidum* seeds on the soil surface from burning 9 t/ha of stubble compared to 3 and 6 t/ha of residue. Davidson (1994) also related the quantity of stubble burnt with temperature and duration of the heat generated, however, this was not found in experiment 2 (Table 5.6). As stated above, quantity of stubble is not the only factor which dictates the temperature produced by a burn, therefore it is not surprising to find differing results between experiments.

As a weed management strategy in the future, the results from experiment 2 for reducing *Avena* spp. seeds through burning crop stubble are encouraging. This is because farmers will adopt improved crop management practices, resulting in greater crop yields and therefore larger quantities of stubble will be available to be burnt (given the straw is not baled). In addition, a heavy stubble is more likely to cover a greater proportion of ground, ensuring a more uniform burn and therefore an increased likelihood of *Avena* spp. seed mortality on the soil surface.

5.4.2 Effect of location of *Avena* spp. seeds at stubble burning

The location (microsite) of wild oat seed at burning can also influence the level of seed kill on the soil surface. Seed position may be changed through intensive grazing by livestock, which trample weed seed into the soil, thus potentially reducing seed

mortality from a stubble burn. Also, livestock may consume seed whilst grazing, as demonstrated with *L. rigidum* seed in a pasture over summer (Gramshaw and Stern, 1977). However, in experiment 1, sheep grazing (at six sheep/ha for 88 days) barley crop residues before burning did not significantly reduce seed numbers on the soil surface, or importantly, the level of *Avena* spp. seed kill (Table 5.3). This outcome is significant given that the grazing of crop stubble by livestock is an integral part of southern Australian farming systems. Although sheep did not significantly reduce stubble quantity in this experiment (Table 5.3), crop residues are considered a valuable feed source for livestock over the summer-autumn period. Farmers who retain their stubbles and do not burn them, rely on livestock to accelerate stubble breakdown, thus improving residue flow through cultivation and seeding equipment at sowing time.

While sheep grazing stubble prior to burning had no affect on wild oat seed kill, soil type may influence the location of *Avena* spp. seed and thus the level of seed mortality on the soil surface from burning. Research by Somody *et al.* (1985) determined that soil cracking differs with soil type, thus affecting the degree of self-burial by *Avena* spp. seeds. Clearly, a larger proportion of seed would escape a stubble burn on a cracking type soil (eg. heavy self-mulching clay), or one constituting loose top soil, compared to a harder setting type. All experiments indicated that viable *Avena* spp. seeds on the soil surface may be reduced through burning, except for experiment 3, when in 1994 and 1995 wild oat seed numbers were not significantly affected (Table 5.10). Experiment 3 was conducted at Roseworthy on a solonised brown soil, whilst experiments 1 and 2 were undertaken at Kapunda on a red-brown earth. Based on visual assessment of each soil type and a description by Northcote *et al.* (1975), it is likely that the Roseworthy soil would provide a preferred environment for the self-burial of wild oat seeds. Northcote *et al.* (1975) characterises the A horizon of a red-brown earth as 'hard setting' (when dry), whilst a solonised brown soil is 'usually loose and powdery'. Therefore *Avena* spp. seeds at Roseworthy may have been better protected from the effects of a burning cereal stubble, compared to the heavier soil at Kapunda. However, the non significant seed mortality result in 1994 and 1995 is probably also associated with the low quantity of stubble burnt and the high variability within pre- and post burn seed quantities (Table 5.10).

5.4.3 Effect of stubble burning on *Avena* spp. plant emergence

Although viable *Avena* spp. seed numbers on the soil surface were generally reduced by crop stubble burning, this did not necessarily reduce wild oat plant emergence following the burn. In experiment 2, stubble burning killed more than 80% of the surface seed (Table 5.5), however, plant emergence after the stubble burn remained unaffected (relative to the no burn treatment) (Table 5.8). In experiment 1, burning crop stubble approximately halved the number of *Avena* spp. seeds on the soil surface, yet wild oat plant emergence following the burn was significantly greater on the burn versus no burn plots. In this case, the effect of burning on the surviving seeds was to partially relieve seed dormancy, causing a five fold increase in seed germinability (Table 5.4) - thus explaining the increase in wild oat emergence. The stimulation of surface seed germination after stubble burning has been documented by various authors (Viel, 1963; Whybrew, 1964; Wilson and Cussans, 1975).

In contrast with experiment 1, the germinability of *Avena* spp. seeds in experiments 2 and 3 were reduced following the burn (Tables 5.7 and 5.11). For experiment 3, burning of crop stubble in 1994 did not stimulate plant emergence, as indicated by measurements undertaken on 12/8/94 (Table 5.9). In this case, burning most likely did not generate a critical heat intensity to affect the dormancy of *Avena* spp. seeds and therefore influence plant emergence. In 1995 and 1996 the emergence of wild oats could not confidently be compared between treatments, due to differential seed bank levels.

5.4.4 Effect of stubble management on *Avena* spp. production

Experiment 3 was undertaken to determine the effect of burning crop stubble and other residue management practices, on the seed production of *Avena* spp. over a three year period. Although stubble burning resulted in a reduction of the *Avena* spp. seed bank compared to the no burn treatments, the practice did not prevent wild oat population growth (Figure 5.1). This agrees with UK studies (Whybrew, 1964; Wilson and Cussans, 1975) that crop stubble burning, alone, will not prevent an *Avena* spp. population increase.

Apart from the effect of burning on wild oat seed production, the retained and baled treatments can be directly compared to determine if the amount of wheat residue

differentially affected seed bank levels (as speculated by Purvis, 1990). The results demonstrated that quantity of stubble had no influence on the seed production of wild oats after three years of continuous cropping (Figure 5.1).

5.4.5 Conclusion

The research described in this chapter aimed at determining the effect of burning residues from cereal crops as a control method for wild oats. The experiments undertaken confirmed that the technique does reduce *Avena* spp. on the soil surface, with excellent control resulting in some cases. Furthermore, stubble burning can stimulate plant emergence of those wild oat seeds that survived the burn. From a practical viewpoint this can be advantageous as seed banks may be further depleted. This is because seedlings can be killed with a knockdown herbicide or cultivation before a late seeded crop is sown. Also a greater plant kill of wild oats would be achieved if an in-crop avenacide was used.

The burning of crop stubble remains one of the few cultural techniques which can be utilised for *Avena* spp. control in continuous cropping systems. This is important given the development of herbicide resistance has necessitated the use of cultural methods for the sustainable control of wild oats. However, regardless of its value as a control measure, stubble burning is generally discouraged in southern Australia because of the recognised benefits of stubble retention. Conversely, periodic burning does have a place for disease management, so if disease and weed pressures coincide (especially if herbicide resistant wild oat plants have set seed), burning may be a useful part of an IWM strategy, particularly on heavy soil types where the potential for soil erosion is low.

Chapter 6

6. The effect of flamprop-*m*-methyl on reducing seed production of *Avena* spp. and the presence of resistant individuals in a previously unselected field population

6.1 Introduction

Weed management has traditionally concentrated on killing weedy plants in order to minimise yield losses from weed competition, with little regard to the minimisation of populations (Medd *et al.*, 1995). While the vegetative production of weeds infesting the crop determine their impact on crop yield during the current year, the seeds added to the seed bank can have a much more persistent effect in the years ahead (Andersson, 1995). Uncontrolled weeds often produce many seeds, resulting in stable or increasing seed populations in the soil, or the establishment and spread of a species in previously uninfested areas (Isaacs *et al.*, 1989).

In many weed species, seed production and seed viability can be reduced by herbicide applications, especially when applied at or near flowering (Fawcett and Slife, 1978; Biniak and Aldrich, 1986; Isaacs *et al.*, 1989). In southern Australia, the normally non-selective herbicide paraquat is widely utilised in pulse crops to specifically reduce *L. rigidum* seed production (crop-topping), with application occurring at the post anthesis stage of *L. rigidum* (Gill, 1996; Matthews and Powles, 1996). Medd and Pandey (1993) urge the development of technology that directly controls seed production of *Avena* spp. in-crop would enable *Avena* spp. populations to be more efficiently regulated.

The extended emergence pattern of wild oats contributes in part to the inability of early applied avenacides to prevent wild oat seed production in crops. Most ACCase inhibitors have limited residual activity and a single early season application does not control successive flushes of weeds. Clearly, the choice of herbicide and timing of application is crucial in the reduction of *Avena* spp. seed production and replenishment of seed banks. Research in northern New South Wales has

demonstrated that the herbicide flamprop-methyl, applied at the early tiller elongation growth stage of *Avena* spp. successfully controls seed production in wheat crops (Medd *et al.*, 1992). Similarly, Wilson (1979b) in Queensland found that flamprop-methyl applied at the boot stage drastically reduced wild oat seed set. However, little is known of the efficacy of flamprop-methyl under the cooler growing season conditions of southern Australia.

A second key component relating to the use of herbicides is herbicide resistance. Its evolution can be attributed to a variety of factors (see 2.5.2), including the initial frequency of herbicide resistant individuals. It is commonly held that herbicide resistant weeds occur naturally in populations at very low frequencies (Jasieniuk *et al.*, 1996). Individual plants resistant to a given herbicide in a previously untreated weed population (that would normally be controlled by that herbicide) have been generally assumed to be in the range of 1×10^{-5} to 10^{-12} (Gressel, 1986; Gressel and Segel, 1990; Maxwell and Mortimer, 1994; Powles *et al.*, 1997). Few studies have established empirical values for the frequency of resistant individuals prior to initial herbicide use. Darmency and Gasquez (1990) determined that the frequency of triazine resistant individuals in *Chenopodium album* ranged from 1×10^{-4} to 3×10^{-3}, whilst Matthews (1996) found an average frequency of 1×10^{-2} diclofop-methyl resistant individuals in *L. rigidum* farm populations. These figures are considerably higher than the non-empirical values assumed. A study undertaken by Putwain *et al.* (1984) examined the selection intensity of flamprop-isopropyl (a different isomer to flamprop-methyl) on *A. fatua* populations. The authors found, through the measurement of plant fecundity, flamprop-isopropyl exerted a low selection intensity for resistance. It was suggested that the level of intensity would not result in a rapid response selection to flamprop-isopropyl, even in a population containing high genetic variance in herbicide sensitivity.

In Australia, flamprop-methyl is used for the control of *Avena* spp. in wheat, triticale and safflower. It is classed as an aminopropionate and has a different mode of action to ACCase inhibitors. From the perspective of herbicide resistance management this is valuable since flamprop-methyl can be rotated with other herbicide groups to help slow the onset of herbicide resistance in wild oats. However, the use of flamprop-methyl to minimise and control ACCase inhibitor resistant *Avena* spp. populations,

and its potential to reduce seed production may encourage increased usage throughout southern Australia. Repeated applications of a single herbicide, or herbicides with a common mode of action, provides the necessary selection intensity to shift weed populations toward high frequencies of resistant individuals (Murray *et al.*, 1995). It is therefore important to assess the capacity of *Avena* spp. to respond to selection intensity imposed by the application of flamprop-methyl.

This chapter reports the results of studies (experiments 1-3) designed to determine the effect of timing of flamprop-*m*-methyl (an isomer of flamprop-methyl) application on *Avena* spp. seed production. The timing of application ranges from early post emergence in wild oats, to the late booting growth stage. In a separate study (experiment 4), the presence of resistant individuals in a field population of *Avena* spp. was determined after exposure to flamprop-methyl.

6.2 Materials and methods

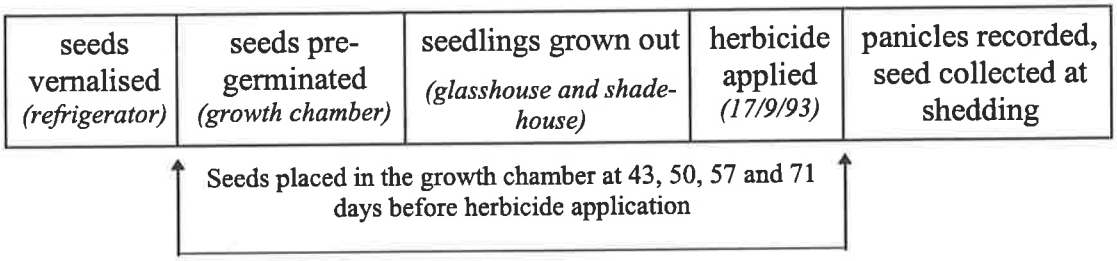
Various studies were conducted at Roseworthy and Auburn (34°02' S, 138°41' E) in the mid-north of South Australia. In all experiments, *Avena* spp. populations were sprayed with flamprop-*m*-methyl (*N*-benzoyl-*N*-(3-chloro-4-fluorophenyl)-D-alanine, Mataven L®, 75 g a.i./l, Cyanamid) or flamprop-methyl (*N*-benzoyl-*N*-(3-chloro-4-fluorophenyl)-DL-alanine, Mataven 100®, 100 g a.i./l, Cyanamid). This was undertaken using a hand-held boom sprayer that delivered 121-139 l/ha (depending on the experiment) of water, at a pressure of 275 kPa. In experiment 4, a trailing boom sprayer was also utilised for the field component of the study. All populations were 'herbicide susceptible', apart from the field population at Auburn (experiment 3) which was resistant to ACCase inhibitors. In all experiments, *Avena* spp. (plant and tiller) and wheat growth stages were determined using the Zadocks decimal growth stage (Zadoks *et al.*, 1974). Statistical procedures were undertaken using Genstat 5 and analysis performed using real or transformed data, depending on the distribution of variance from the mean.

6.2.1 Experiment 1

A pot study was undertaken at Roseworthy in 1993 to determine the effect of flamprop-*m*-methyl on *A. ludoviciana* plants of different ages. In addition, the

influence of flamprop-*m*-methyl on seed production at different tiller growth stages was defined. The experiment was structured as a completely randomised design (CRD), with four plant age groups (43, 50, 57 and 71 days) and three replications. A 'plant age group' refers to the length of time from seeds entering the laboratory growth chamber until flamprop-*m*-methyl was applied. The four plantings were staggered to permit the spraying of all plants on the same day. Graphic representation of the experimental procedure is depicted in Figure 6.1.

Figure 6.1 Methodology followed for experiment 1.



Several hundred *A. ludoviciana* seeds were put in containers containing a solution of 0.6% agar and 0.1% thiram, moistened with water and transferred to a refrigerator set at 4°C for a period of seven days for vernalisation. On 8/7/93, seeds were placed in a growth chamber maintained at a 12 hour, 18°C light / 12 hour, 15°C dark regime. Soon after leaf emergence, seedlings were randomly selected and transplanted into 18 cm diameter x 13 cm deep pots containing recycled potting soil. Two seedlings were sown into each of 12 pots (one pot of two plants = one replication). These plants represent the 71 day old plant age group. The procedure was repeated for seeds placed initially in the refrigerator and then the growth chamber on 22/7, 29/7 and 5/8/93 (57, 50 and 43 day old plants respectively).

After each planting, pots were moved to a glasshouse (to ensure favourable early growing conditions) and then to an outdoor shade-house. Pots were randomly placed in three blocks and at weekly intervals moved between blocks to ensure uniform plant growth throughout the experimental period. In addition, all pots were fertilised and watered at regular intervals (watering ceased on 31/10/93 - the end of the normal growing season at Roseworthy).

At spray application, each tiller from every *A. ludoviciana* plant was counted and grouped into one of four (vegetative, elongating, booting or heading) developmental growth stages. Different colour plastic bands were loosely wrapped around the base of each tiller to identify its growth stage. This was undertaken to ensure seed production could be calculated for each tiller type, irrespective of the age of plant at spraying. Flamprop-*m*-methyl application occurred on 17/9/93. Pots were randomly selected from each age group of plants and assigned to one of four treatments; flamprop-*m*-methyl at half, full and 2x recommended rates (112.5, 225 and 450 g a.i./ha respectively) for Australian broadacre crops, and an untreated control. Each treatment within a plant age group comprised three replicates.

As the *A. ludoviciana* plants matured, seeds in each pot were collected and bulked according to their tiller growth stage at spraying. Seed was tested for viability by the 'pinch test' (Appendix 2). In addition, the number of tillers which had reached the panicle (heading) stage on 4/11/93 (48 days after spraying) was recorded.

Statistical analysis was performed as a CRD, with a factorial treatment structure ((treatment x plant age) or (treatment x tiller growth stage)). Factorial analysis was also undertaken on the herbicide treatments only (without the untreated control), to determine the importance of application rate and tiller growth stage on *A. ludoviciana* seed production.

6.2.2 Experiment 2

A field experiment was conducted at Roseworthy in 1993 to determine the effect of flamprop-*m*-methyl on *Avena* spp. at the late booting growth stage (defined as an early crop-topping procedure). The experiment was undertaken in a commercial crop of wheat (cv. Excalibur) sown on 5/7/93 at a seeding rate of 80 kg/ha. On 29/9/93, an area infested with approximately 50 *A. fatua* plants/m^2 was split into a RCBD, with four replications and 2 x 10 m plots. Flamprop-*m*-methyl was sprayed at half and full recommended rates (112.5 and 225 g a.i./ha respectively), and compared to an untreated control. At spray application the plant density of *A. fatua* was recorded and 40 plants (10/replicate) were randomly selected to determine the average *A. fatua* (plant and tiller) growth stage. In addition, 20 wheat plants (five/replicate) were randomly chosen to determine the average growth stage of the crop at spraying.

On 10/11/93 (42 days after spraying), the number of tillers which had developed into panicles was determined from three (0.24 m^2) quadrats per plot. On 13/12/93 (after *A. fatua* seed shed and wheat maturity), an industrial vacuum cleaner was used to collect the recently shed *A. fatua* seed located on the soil surface. *A. fatua* samples along with heads of wheat were collected from three (0.093 m^2) quadrats per plot to provide yield estimates. The *A. fatua* samples were sieved and sub-sampled and the seed extracted by hand to determine seed production.

The seed viability of *A. fatua* was determined by the 'laboratory test' (Appendix 2). Viability percentages (determined by the ability of seed to germinate after dehusking, pricking and gibberellic acid treatment) were applied to the seed aggregates to determine the number of viable seed. The wheat heads were threshed, and grain yield and 1000 grain weight derived. Statistical analysis was performed as a RCBD with sub-samples for all *A. fatua* data, whilst plot means were compared for the wheat measurements.

6.2.3 Experiment 3

Two field experiments were conducted in 1994 to determine the effect of flamprop-*m*-methyl, applied at different timings, on *Avena* spp. mortality and seed production. Experiments were undertaken in commercial crops of wheat infested with *A. fatua* and *A. ludoviciana*: at Roseworthy in an ACCase inhibitor susceptible population and at Auburn in an ACCase inhibitor resistant population. Both populations were susceptible to flamprop-*m*-methyl. Wheat was sown at Roseworthy, cv. Trident (6/7/94) and cv. Janz at Auburn (4/7/94). The sowing rates were 80 and 100 kg/ha respectively. At both sites, an area infested with *Avena* spp. was selected and split into a RCBD, with four replications and 2 x 10 m plots.

Flamprop-*m*-methyl was applied at two timings (early and late), at half and full recommended rates (112.5 and 225 g a.i./ha respectively), and compared to an untreated control. *Avena* spp. plant density was determined, and 20 wheat and 40 *Avena* spp. plants were evaluated at each herbicide application date to define average wheat and *Avena* spp. (plant and tiller) growth stages. It was determined that timing for the early application of flamprop-*m*-methyl occur within the registered label recommendation (Z13-Z30), whilst the late application be undertaken when

approximately 80% of *Avena* spp. tillers were at the vegetative growth stage and 20% were elongating. This is the optimum timing to achieve maximum seed reduction using flamprop-*m*-methyl in northern New South Wales (R. Medd pers. comm.).

After herbicide application, data was collected as per experiment 2 (6.2.2), including *Avena* spp. panicle numbers (8/11/94 at Roseworthy and 28/10/94 at Auburn), and *Avena* spp. seed production and wheat head numbers (30/11/94 at Roseworthy and 14/12/94 at Auburn). The wild oat samples were sieved and the seed extracted by hand to determine seed production, whilst seed viability was determined by the 'pinch test' (Appendix 2). Statistical analysis was performed as a RCBD with sub-samples for all *A. fatua* data, whilst plot means were compared for the wheat measurements. Multiple comparisons were undertaken using the least significant difference method. In addition, factorial analysis was performed on the herbicide treatments only (without the untreated control), to determine the effect of herbicide timing and rate on wild oat production, and grain yield of wheat.

6.2.4 Experiment 4

An experiment was initiated in 1995 at Roseworthy to determine the presence and initial frequency of any flamprop-methyl resistant individuals in a field population of *Avena* spp. Seed from wild oat plants that survived flamprop-methyl application in the field were re-tested in pots in 1996 to verify survivorship. Flamprop-methyl was evaluated (instead of flamprop-*m*-methyl) since in 1995 flamprop-*m*-methyl was not yet available to Australian farmers.

6.2.4.1 Field selection

The experiment was established on a 1.5 ha site which had never been treated with flamprop-methyl and was known to be infested with *A. fatua* and *A. ludoviciana*. Site preparation included cultivation with a scarifier on 5/5/95 to stimulate weed seed germination, and spraying with glyphosate (at 585 g a.i./ha, 22/5/95) and chlorsulfuron (at 15 g a.i./ha, 19/6/95). Chlorsulfuron was applied to control *L. rigidum* and *Oxalis pes-caprae* which also infested the experimental area (chlorsulfuron is not recommended for controlling wild oats and showed no activity in the field). The site was divided into three (50 x 100 m) replications.

Flamprop-methyl was applied at the recommended rate (450 g a.i./ha) on three occasions (5/7, 12/8, 15/9/95) throughout the growing season. This was to guarantee a high selection intensity was exerted on the *Avena* spp., and to account for the extended emergence pattern of wild oats (thus ensuring all plants were sprayed). At each application date, treatment was conducted twice at the half rate to ensure good herbicide coverage. A 6 m trailing boom sprayer that delivered 58 l/ha of water at a pressure of 200 kPa was used. When flamprop-methyl was first applied, the *Avena* spp. plant density was determined (from 15 (0.1 m^2) quadrats per replicate), whilst at the second and third timings the density of newly emerged, unsprayed *Avena* spp. plants was recorded.

On 15/10/95, a month after the third herbicide application, the survival of *Avena* spp. plants was determined from 12 (0.5 m^2) quadrats per replicate. All survivors were visually affected by flamprop-methyl. Sixty nine (23/replicate) of the most vigorous surviving plants were selected from the experimental area and transferred into pots containing recycled potting soil. The vigorous plants were selected, rather than randomly chosen, since it was thought a 'weak survivor' would be incapable of producing viable seed. Pots were watered as required, and fertilised at regular intervals. As the plants matured their seeds were collected. Seed was kept in their respective 'plant family' and allowed to after-ripen at ambient temperatures (under shelter) at Roseworthy prior to re-testing in 1996.

6.2.4.2 Assessment of plant families in pots

Wild oat seed produced from plants which survived herbicide application were pre-germinated and then transferred to containers before being sprayed with flamprop-methyl. To encourage germination, seeds were dehusked and punctured at the embryo end with a fine dissecting needle. The seeds were then placed in containers containing a solution of 0.6% agar and 0.1% thiram, moistened with water and transferred to a refrigerator set at 4°C for a period of seven days for vernalisation. Samples were then placed in a laboratory growth chamber maintained at a 12 hour, 15°C light / 12 hour, 10°C dark regime. Soon after leaf emergence, seedlings were transplanted into 18 x 10 x 6 cm plastic containers containing recycled potting soil. A maximum of 10 seedlings were sown into each container after which they were moved outdoors and watered as required, and fertilised at regular intervals. From the

end of the normal growing season (31/10/96) until completion of the experiment, watering was restricted to every second day.

Herbicide application occurred on 26/9/96 with plants being sprayed with 450 g a.i./ha of flamprop-methyl using the hand-held boom sprayer. Treatment was undertaken twice at 225 g a.i./ha to ensure good herbicide coverage. A wild oat population known to be susceptible to flamprop-methyl was also sprayed to check herbicide efficacy. On 15/10/96 it was noted that the majority of *Avena* spp. plants were not sufficiently affected (the susceptible controls were slightly more affected) by flamprop-methyl to cause plant death (similar observations were made in the field the previous year), and therefore spraying was repeated. On 26/11/96, all plants were evaluated for survival. *Avena* spp. plants were considered survivors if they produced advanced panicles (from original tillers at 26/9/96) and contained viable seed. Seed viability was determined by applying pressure to seeds (in the panicle) with the thumb and forefinger. Seeds that had reached the milk development stage (>Z70) were recorded as viable, and thus plants were considered resistant to flamprop-methyl.

6.3 Results

6.3.1 Experiment 1 - effect of flamprop-*m*-methyl on different age *A. ludoviciana* plants and tillers

6.3.1.1 Growth stages of *A. ludoviciana* plants at spraying

The average developmental growth stage at herbicide application for each *A. ludoviciana* plant age group represented plants ranging from early elongation to early heading (Table 6.1). These differing tiller proportions made for clear differences between plant age groups at spraying.

Table 6.1 *A. ludoviciana* tiller growth stages and tillers per pot at flamprop-*m*-methyl application.

Plant age (days)	43	50	57	71
Tillers - vegetative (%)	91[†]	64	56	43
Tillers - elongating (%)	9	23	28	21
Tillers - booting (%)	0	13	10	19
Tillers - heading (%)	0	0	6	17
Tillers/pot (nos.)	8	9	9	11

[†]Percentage based on an average of all replicates within each plant age group.

6.3.1.2 Effect on seed and panicle production of *A. ludoviciana*

The application of flamprop-*m*-methyl reduced seed production of *A. ludoviciana* by a minimum of 85% compared to the untreated control (Table 6.2). Seed yield generally increased with *A. ludoviciana* plant age, and a significant interaction with treatment was determined ($P<0.01$). Similarly, analysis performed on the flamprop-*m*-methyl treatments only, identified a herbicide x plant age interaction ($P<0.05$).

Table 6.2 The effect of flamprop-*m*-methyl application on seed production of differing age *A. ludoviciana* plants.

	A. ludoviciana seed production (nos./pot)			
Plant age (days)	43	50	57	71
Untreated control	7.86 (61)[†]	9.68 (93)	13.2 (174)	11.57 (133)
Half rate	0.71 (0)	1.32 (1)	2.58 (6)	4.13 (17)
Full rate	1.94 (3)	1.39 (1)	0.88 (0)	3.41 (11)
2x full rate	0.71 (0)	1.35 (1)	2.4 (5)	4.52 (20)

[†]Values in parentheses indicates back-transformed means, the data being transformed (sqrt (x + 0.5)) prior to ANOVA. Treatment x plant age interaction s.e.d. = 0.831.

The number of *A. ludoviciana* panicles, measured 48 days after spraying, was significantly reduced by all flamprop-*m*-methyl rates, relative to the untreated control (Table 6.3). Separate analysis performed on all treatments, and flamprop-*m*-methyl treatments only, identified a treatment x plant age interaction ($P<0.05$) for each analysis.

Table 6.3 The effect of flamprop-*m*-methyl application on panicle production of differing age *A. ludoviciana* plants.

	A. ludoviciana panicle production (nos./pot)			
Plant age (days)	43	50	57	71
Untreated control	3.06 (8)[†]	3.18 (9)	3.29 (10)	3.63 (13)
Half rate	0.71 (0)	1.0 (0)	1.86 (3)	2.02 (4)
Full rate	1.05 (1)	1.05 (1)	1.05 (1)	2.11 (4)
2x full rate	0.71 (0)	1.17 (1)	1.34 (1)	1.56 (2)

[†]Values in parentheses indicates back-transformed means, the data being transformed (sqrt (x + 0.5)) prior to ANOVA. Treatment x plant age interaction s.e.d. = 0.254.

While there were interactions between herbicide rates and plant age (for both seed and panicle production data) no particular patterns were evident in regard to application rate.

6.3.1.3 Influence of tiller growth stage on seed production of *A. ludoviciana*

Regardless of tiller growth stage, flamprop-*m*-methyl reduced seed production of *A. ludoviciana*, a significant interaction with treatment being determined ($P<0.001$) (Table 6.4). In contrast, analysis performed on the flamprop-*m*-methyl treatments only, identified a growth stage effect ($P<0.001$) where the more advanced tillers still produced seed after chemical treatment. Herbicide application rate had no affect on seed production.

Table 6.4 The effect of flamprop-*m*-methyl application on seed production of differing age *A. ludoviciana* tillers.

	A. ludoviciana seed production (nos./four pots)			
Tiller growth stage	vegetative	elongating	booting	heading
Untreated control	5.5 (241)[†]	4.88 (130)	3.9 (48)	3.42 (26)
Half rate	0.69 (1)	0 (0)	1.52 (4)	2.77 (15)
Full rate	1.63 (4)	0 (0)	1.94 (6)	1.83 (5)
2x full rate	0 (0)	0 (0)	1.57 (4)	3.15 (22)

[†]Values in parentheses indicates back-transformed means, the data being transformed (log (x + 1)) prior to ANOVA. Treatment x tiller growth stage interaction s.e.d. = 0.49.
Data analysed as seed production totals of each tiller growth stage (irrespective of the age of plants at application). Analysis undertaken on numbers of seed produced from four pots, since seed production from a single herbicide treated pot was extremely low.

Since flamprop-*m*-methyl application rate (over the range applied) did not differently affect the seed production of *A. ludoviciana*, the herbicide treatments were averaged and compared to the untreated control (Figure 6.2). The analysis confirmed an interaction with tiller growth stage ($P<0.001$).

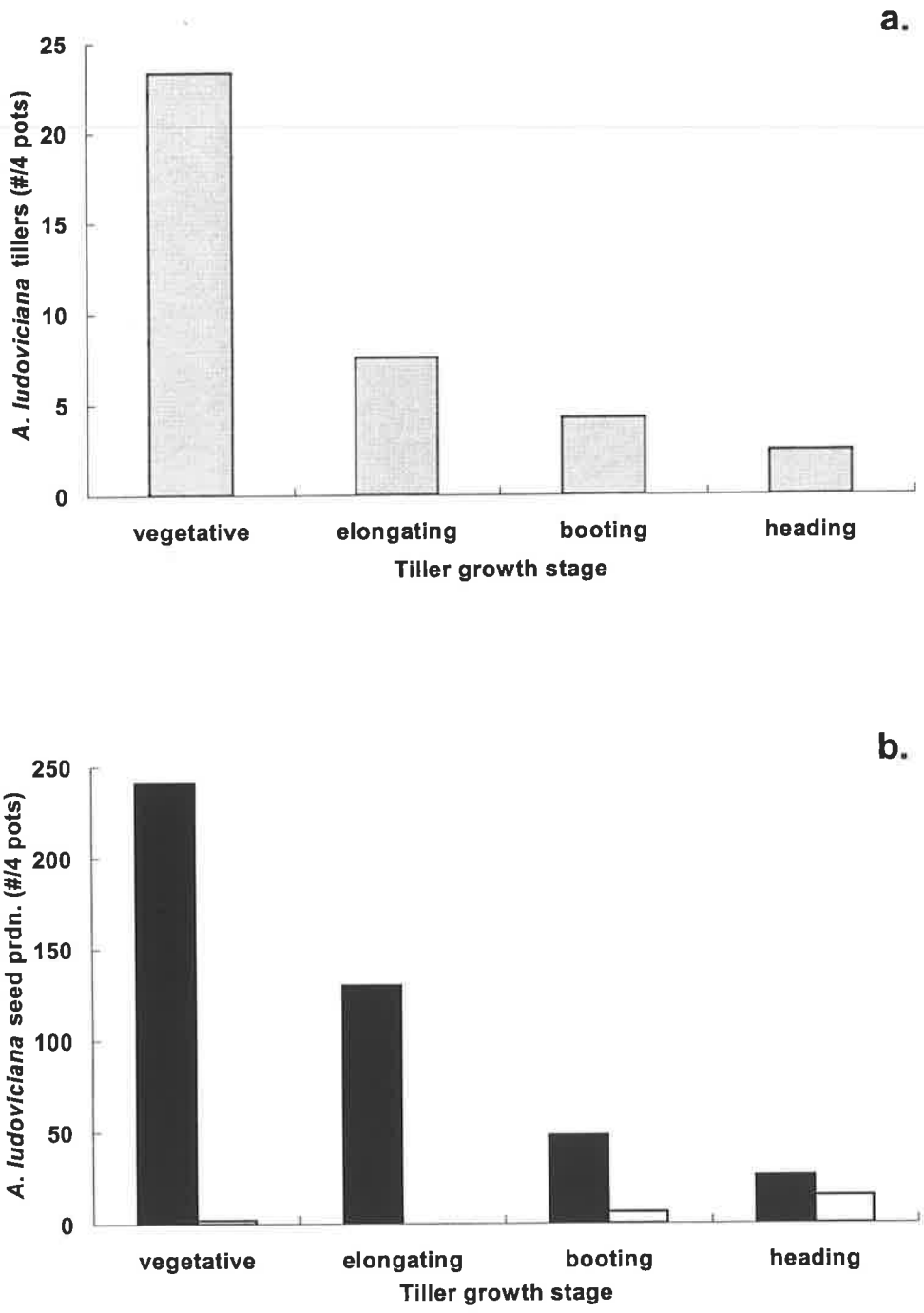


Figure 6.2 The effect of flamprop-*m*-methyl (mean of three rates) on *A. ludoviciana* seed production: (**a**) tiller totals (nos./four pots) representing different growth stages at herbicide application and (**b**) the corresponding effect (on those tiller groups) of flamprop-*m*-methyl (□) on seed production, relative to an untreated control (■). Back-transformed means are illustrated in **b**., the data being transformed (log (x + 1)) prior to ANOVA and producing a flamprop-*m*-methyl x tiller growth stage interaction (P<0.001).

6.3.2 Experiment 2 - effect of flamprop-*m*-methyl on *A. fatua* at the late booting growth stage

6.3.2.1 Plant growth stages at spraying

The average growth stage of *A. fatua* plants at herbicide application was late booting (Table 6.5). However, plants were highly variable in their development, ranging from Z23 to Z22/58 (data not presented). The growth stage of wheat at spraying was Z23/38 - the late elongation stage.

Table 6.5 *A. fatua* growth stage and plant density at flamprop-*m*-methyl application.

Plant growth stage	Tiller growth stage (%)				Plant density
(Zadocks)	vegetative	elongating	booting	heading	(plants/m^2)
24/47	38	25	20	17	46

6.3.2.2 Effect on seed production of *A. fatua* and grain yield of wheat

The application of flamprop-*m*-methyl did not significantly reduce *A. fatua* seed production, with seed yield being highly variable within treatments (Table 6.6). Likewise, the numbers of panicles post spraying, and grain yield of wheat were not significantly affected (Table 6.6). In addition, flamprop-*m*-methyl application had no affect on wheat head totals at grain harvest or 1000 grain weight of wheat (data not presented).

Table 6.6 The effect of flamprop-*m*-methyl application on seed production of *A. fatua* and grain yield of wheat.

	A. fatua seed production (nos./m^2)		*A. fatua* panicles (nos./m^2)	Wheat grain yield (t/ha)
	mean	range		
Untreated control	1450[†]	113-2722	141	3.56
Half rate	584	51-1673	105	4.42
Full rate	577	40-1513	96	4.06
s.e.d	375	-	27	0.52
Significance level	ns	-	ns	ns

[†]Indicates data for seed production was transformed (sqrt (x + 0.5)) prior to ANOVA. The transformation did not affect the significance level, therefore actual means are presented.

6.3.3 Experiment 3 - effect of flamprop-*m*-methyl on *Avena* spp. at different application timings

6.3.3.1 Plant growth stages at spraying

The developmental stages of *Avena* spp. at herbicide application were similar for their respective timings (early and late) at each site, whilst the density of wild oat plants at Auburn were substantially higher compared to Roseworthy (Table 6.7).

Table 6.7 Wheat and *Avena* spp. growth stages and *Avena* spp. plant densities at flamprop-*m*-methyl application.

	Roseworthy		Auburn	
	Early	Late	Early	Late
Application date	23/8/94	8/9/94	6/9/94	24/9/94
Wheat growth stage (Zadocks)	14.7/22	16.5/22	15.2/22	6.5/22
Avena spp. plant growth stage (Zadocks)	14/21	15/21	13.1/21	14.5/21
Avena spp. tiller growth stage				
- vegetative (%)	100	72	100	81
- elongating (%)	0	28	0	19
Avena spp. density (plants/m^2)	30	37	166	172

6.3.3.2 Effect on seed production of *Avena* spp.

At Roseworthy (ACCase inhibitor susceptible site) and Auburn (ACCase inhibitor resistant site), flamprop-*m*-methyl reduced seed production of *Avena* spp. relative to the untreated control, irrespective of timing or rate, with most treatments being statistically significant (Table 6.8). Similarly, flamprop-*m*-methyl reduced *Avena* spp. seed weight and panicle numbers (Table 6.8). Flamprop-*m*-methyl applied at the full rate (225 g a.i./ha) and late timing (early *Avena* spp. tiller elongation) was the most effective treatment at each site, reducing *Avena* spp. seed production by an average of 97% (Table 6.8).

Flamprop-*m*-methyl did not always significantly reduce *Avena* spp. production (Table 6.8). This may be attributed to the high data variability within treatments. The factorial analysis (performed on the herbicide treatments only), identified a timing effect at Auburn. Flamprop-*m*-methyl application at the later timing significantly

reduced *Avena* spp.; seed totals ($P<0.05$), seed weight ($P<0.01$) and panicle numbers ($P<0.05$) compared to the early timing. At Roseworthy, there was no difference between early and late timing. In addition, at both sites the full application rate of flamprop-*m*-methyl reduced *Avena* spp. panicle numbers ($P<0.05$) compared to the half rate (Table 6.8).

Table 6.8 The effect of flamprop-*m*-methyl application on seed production of *Avena* spp. and grain yield of wheat.

	Avena spp. seed prodn. (nos./m^2)	*Avena* spp. seed weight (mg/m^2)	*Avena* spp. panicles (nos./m^2)	Wheat grain yield (t/ha)
Roseworthy				
Untreated control	470^{b}	8650^{b}	36^{c}	0.73
Early timing + half rate	19^{a}	310^{a}	18^{ab}	0.70
Early timing + full rate	14^{a}	220^{a}	5^{a}	0.91
Late timing + half rate	29^{ab}	590^{a}	15^{bc}	0.74
Late timing + full rate	7^{a}	150^{a}	5^{a}	0.81
s.e.d	‡	‡	‡	0.15
Significance level	$P<0.05$	$P<0.01$	$P<0.01$	ns
Auburn				
Untreated control	623^{c}	13920^{c}	77^{b}	2.98
Early timing + half rate	133^{b}	2890^{b}	58^{b}	2.87
Early timing + full rate	142^{bc}	3030^{b}	27^{a}	3.11
Late timing + half rate	61^{b}	1110^{ab}	28^{a}	3.13
Late timing + full rate	31^{a}	530^{a}	17^{a}	3.37
s.e.d	‡	‡	10	0.28
Significance level	$P<0.01$	$P<0.001$	$P<0.001$	ns

Values in columns not followed by the same common letter differ significantly ($P<0.05$).

‡Indicates data was transformed (log (x + 1)) prior to ANOVA. Actual data is presented, as the high variability within particular treatments meant back-transformed values did not satisfactorily represent their respective actual means.

6.3.3.3 Effect on grain yield of wheat

Flamprop-*m*-methyl application, irrespective of timing or rate, did not significantly affect grain yield of wheat at Roseworthy or Auburn (Table 6.8). Similarly,

flamprop-*m*-methyl had no affect on wheat head totals at grain harvest, or 1000 grain weight of wheat (data not presented). Neither early and late timing, or low and high rate affected wheat grain yield, head totals or grain weight.

6.3.4 Experiment 4 - presence of *Avena* spp. individuals resistant to flamprop-methyl in a previously unselected field population

6.3.4.1 Field populations of *Avena* spp. prior to flamprop-methyl application

The density of newly emerged *Avena* spp. at each herbicide application declined rapidly throughout the growing season (Table 6.9). A total of 245 plants/m^2 (3,675,000 plants estimated for 1.5 ha) were treated with flamprop-methyl - 70% of plants could have received three applications (1350 g a.i./ha), 29% two applications (900 g a.i./ha), and 1% one application (450 g a.i./ha).

Table 6.9 Density of newly emerged *Avena* spp. plants in the field at each flamprop-methyl application.

Application date	5/7/95	12/8/95	15/9/95
Avena spp. density (unsprayed plants/m^2)	171	72	2

6.3.4.2 *Avena* spp. survival after flamprop-methyl application

It was determined that 5.5 *Avena* spp. plants/m^2 (82,500 plants estimated for 1.5 ha) survived the application(s) of flamprop-methyl in the field. Therefore, only 2% of plants survived the herbicide treatment. These surviving plants were visually affected by flamprop-methyl, but were classified as survivors as they produced new tillers after herbicide application. Of the 69 surviving plants collected from the field and grown in pots to maturity, only 36 produced viable seed. These were maintained as individual families and seedlings from these single plant families were treated in pots with flamprop-methyl. The number of seedlings tested for each plant family varied up to 23, with the mean being five. Eight of the 36 plant families showed varying levels of resistance to flamprop-methyl (Table 6.10). The susceptible controls were killed

Table 6.10 Survival of seedlings from single plant families (produced from *Avena* spp. plants that survived flamprop-methyl application(s) in the field), following two applications of flamprop-methyl in pots.

Single plant families (nos. sprayed)	Average seedling survival (%)
28	0.0
8	20.4 (7.1-50.0)†

†Denotes the range of seedling survival from the resistant plant families.

6.4 Discussion

6.4.1 Effect of application timing on reducing *Avena* spp. seed production

Several experiments were undertaken to determine the effect of application timing of flamprop-*m*-methyl on *Avena* spp. seed production. It was found that the timing of flamprop-*m*-methyl application was critical in determining the numbers of seed produced. While this research used both *Avena* species and mixtures, there was no evidence of differences with herbicide efficacy. Field studies conducted in 1994 in wheat crops infested with wild oats (experiment 3) demonstrated that application at the early tiller elongation stage of *Avena* spp. produced the greatest reduction in seed yield, with treatment at the full rate (225 g a.i./ha) reducing seed production by 97% (Table 6.8). When flamprop-*m*-methyl was applied to *A. ludoviciana* plants (43 days old) at the beginning of elongation in pots (experiment 1), seed production was limited by a similar percentage (Table 6.2). In addition, flamprop-*m*-methyl was highly effective on elongating tillers, regardless of plant age (Table 6.4 and Figure 6.2). This agrees with Jeffcoat *et al.* (1977), who determined in glasshouse studies that flamprop-methyl (the parent isomer of flamprop-*m*-methyl) has maximum activity when the main stem of *Avena* spp. is beginning to elongate. Likewise, Cook *et al.* (1993) showed that flamprop-methyl is effective in reducing seed production of wild oats when applied at a similar growth stage.

While the effects of flamprop-methyl on *Avena* spp. control is well known, there is little published data on the effect of flamprop-*m*-methyl, especially on the reduction of wild oat seed yield at the late post emergence growth stage. Comparative studies with flamprop-methyl in Canada (Wright and Morrison, 1983; Friesen, 1987) have

shown that both herbicide isomers achieve similar levels of *Avena* spp. control. Thus the efficacy of flamprop-*m*-methyl has been regarded as analogous to flamprop-methyl. Various timing of application studies from overseas have shown that application of flamprop-methyl as a late post emergent treatment (late tillering-early elongation growth stage of *Avena* spp.) is more successful in reducing *Avena* spp. seed production compared to an early post emergent treatment (Baldwin and Livingston, 1976; Smith and Livingston, 1978; Lopez, 1983). This concurs with results from experiment 3 at the Auburn site, where the late application flamprop-*m*-methyl treatments substantially reduced *Avena* spp. seed production compared to the early timing (early tillering of *Avena* spp.). At Roseworthy there was no significant affect of timing. This may be attributed to the short growing season during 1994. Rainfall at Roseworthy throughout the 1994 growing season (April to October) was reduced by 45% compared to the long term average (Appendix 1).

Application of flamprop-*m*-methyl during early elongation of wild oats produced the greatest reduction in seed production, whilst treatment at later timings gave lower control. This was best illustrated in the pot experiment, which gave a precise measure of herbicide efficacy on *A. ludoviciana* plants at specific developmental and tiller growth stages. The 71 day old plants, where 36% of tillers were either at the booting or heading stage when sprayed (Table 6.1), produced significantly more seed compared to the younger treated plants (Table 6.2). The seed yield of heading tillers (regardless of plant age) was reduced by 42% (mean of three rates) relative to the untreated control, a significantly lower reduction than the other less mature tiller groups (Figure 6.2). These results demonstrate that the majority of seed produced were derived from the oldest *A. ludoviciana* plants, and from the oldest tillers (heading stage) when treated.

The 71 day old *A. ludoviciana* plants in pots were at a similar growth stage to the *A. fatua* plants treated in experiment 2. Experiment 2 was undertaken to evaluate flamprop-*m*-methyl as an early crop-topping practice, with application occurring at the late booting stage in *Avena* spp. and prior to anthesis. However, flamprop-*m*-methyl did not significantly decrease seed production compared to the untreated control, even though a downward trend seemed apparent (Table 6.6). This may be attributed to the high variability within treatments (Table 6.6), caused by an uneven distribution of *A. fatua* plants over the experimental site. 'Patch variation' is an acknowledged feature of

Avena spp. within a field (Thornton *et al.*, 1990; Gonzalez-Andujar and Perry, 1995). Nevertheless, even if the reduction in seed yield was significant, the use of flamprop-*m*-methyl as an early crop-topping practice is not advocated given the high proportion of viable wild oat seed still produced.

Clearly, the timing of flamprop-*m*-methyl application is critical in determining *Avena* spp. seed production, and according to the research described here is more important than the rate of application. For both field experiments, analysis performed on the herbicide treatments only, found no significant difference in seed yield between half and full rates. Whilst in experiment 3, where three rates were compared, interactions between herbicide rates and plant age were identified, but no particular patterns were apparent in regard to dose rate.

6.4.2 Effect of application timing on grain yield of wheat

Unlike the control of *Avena* spp. seed production, timing (and rate) of flamprop-*m*-methyl did not affect the grain yield of wheat (Tables 6.6 and 6.8). This result was not unexpected in experiment 2, given the delayed timing of application. However, in experiment 3 (at both sites), the early timing treatment did not produce a yield benefit, relative to the untreated control, let alone compared to the late applied treatment. This is in contrast to the knowledge that the early removal of wild oats favours the enhancement of grain yield (Medd, 1997), and wild oats consistently cause substantial reductions in crop yield throughout southern Australia (see 2.3.2). A lack of response for grain yield at the Roseworthy site may be attributed to the 1994 drought (Appendix 1). However, at Auburn, given reasonable rainfall throughout the growing season (Appendix 1) and a heavy infestation of *Avena* spp. (>166 plants/m^2), it was thought a yield increase would result after *Avena* spp. plants were controlled by flamprop-*m*-methyl.

6.4.3 Practical implications for the use of flamprop-*m*-methyl

The research described here using flamprop-*m*-methyl in southern Australia supports the work by Medd *et al.* (1992) in northern New South Wales which established that flamprop-methyl applied late post emergence can greatly reduce in-crop *Avena* spp. seed production. As the persistence of *Avena* spp. populations in cropping systems is due to the annual input of new seed, the use of post emergence herbicides applied late

is thus an important strategy to minimise the replenishment of seed banks (Medd *et al.*, 1992; Medd *et al.*, 1995).

From the point of view of agronomic management, timing of herbicide application is critical for reducing weed seed production and enhancing grain yield. Flamprop-*m*-methyl is recommended to be applied at the Z13-Z30 growth stage. Research described here suggests treatment towards the end of this range gives greater wild oat control, however, according to the literature, early removal of wild oats is desirable to minimise crop losses due to competition. Thus, the use of flamprop-*m*-methyl may be a compromise between adequate control of wild oat seed production (vegetative stage of application) with higher crop yields but increased wild oat reinfestation potential, and exceptional control of seed production (early wild oat tiller elongation stage of application) but smaller yield increases as a result of late removal of wild oat competition. Flamprop-*m*-methyl used at the early elongation stage is a management option specifically aimed at minimising *Avena* spp. seed production. However, it does not discount the need to undertake yield conservation measures of pre- or early post emergence application of herbicides, particularly amongst heavy *Avena* spp. infestations.

In southern Australian farming systems, weed management also focuses on minimising herbicide resistance in wild oats. Flamprop-*m*-methyl can be used to help slow the onset of resistance to herbicides within any single chemical group, by rotation with herbicides of alternative groups. This is of particular importance in southern Australia as resistance has evolved to ACCase inhibitors - the dominant herbicide group used for wild oat control. However, the rotation of ACCase inhibitors with other herbicide groups will prolong their (and other groups) efficacy. In addition, flamprop-*m*-methyl has the capability to directly control *Avena* spp. plants which have developed resistance to ACCase inhibitors, as demonstrated at Auburn in experiment 3 (Table 6.8).

6.4.4 Presence of *Avena* spp. resistant individuals in a previously unselected field population

Avena spp. populations have developed resistance to the flamprop type herbicides overseas (see 2.5.5.2), however, there are no documented cases of resistance in Australia. The aim of experiment 4 was to determine the presence and initial frequency of any flamprop-methyl resistant individuals within a previously unselected field population. This knowledge is important since the initial frequency of resistance influences, to varying degrees, the number of generations for resistance to evolve in a weed population. The application of flamprop-methyl in the field determined that 98% of *Avena* spp. plants were killed, leaving 5.5 plants/m^2 as survivors. This is a considerably high level of survival after three applications of flamprop-methyl. However, plant survival is dependant on many environmental factors at the time of application, due to its affect on herbicide uptake and efficacy (Morrison, 1983). If the field component of the experiment was conducted amongst a competitive crop and under warmer growing season conditions, increased wild oat plant kill would most likely result, since these conditions enhance flamprop-methyl performance (Jeffcoat *et al.*, 1977; Sharma and Vanden Born, 1983). Even though the most vigorous surviving wild oat plants were collected from the field, only 36 of the 69 survivors produced some viable seeds. Nevertheless, the non random selection of survivors meant that the exact level of field resistance could not be stated. In addition, a limited sample size was used (average of five seedlings per plant family) to verify resistance in pots.

From a practical viewpoint, this experiment highlighted the difficulty in quantifying the frequency of flamprop-methyl resistant individuals within a field. Although many susceptible plants remained after application, the presence of resistance was detected (Table 6.10), with resistance most likely existing at a low frequency. This low level, coupled with the importance of *Avena* spp. plant growth stage and environmental conditions at herbicide application, are possible reasons why a high proportion of susceptible plants remained after flamprop-methyl treatment.

6.4.5 Conclusion

The main focus of this chapter aimed at determining the effect of timing of flamprop-*m*-methyl application on *Avena* spp. seed production. Several studies proved that application timing is critical in controlling numbers of seed produced from wild oat plants. Application at the early tiller elongation stage of *Avena* spp., a timing slightly later than recommended for post emergent avenacide treatment, gave the best results and significantly reduced seed yield. This is pertinent, given one of the main failings of early applied ACCase inhibitors is their inability to control seed production. Thus the technique has the potential to minimise the replenishment of seed banks, hence enabling *Avena* spp. populations to be more efficiently regulated within crops in southern Australia.

Chapter 7

7. General discussion

Wild oats are widely spread throughout southern Australia and are one of the regions most successful and economically damaging crop weeds. To effectively manage *Avena* spp. in farming systems it is essential an IWM program be adopted that minimises seed bank populations. The mid-north of South Australia has farming systems that are typical of those found across much of southern Australia. Therefore research conducted in this thesis provides a basis for specific suggestions in relation to the short and long term management of wild oats for southern Australian farming systems.

7.1 Seed production of *Avena* spp.

The field survey (Chapter 3) found that 90% of cropping fields in the mid-north of South Australia contained wild oats, with one third of fields having infestations of more than 10 plants/m^2 (Table 3.1). This demonstrates that not only are wild oats a serious weed of crops in this region, but as the survey was undertaken just prior to harvest, that relatively high numbers of *Avena* spp. plants remained uncontrolled in many fields. Given that each uncontrolled wild oat plant growing in a cereal crop produce about 40 to 50 seeds (Cussans, 1976), it is clear that the observed populations contributed to the seed bank (especially considering that wild oat plants shed their seed early and only a small proportion of seed can be caught in the harvest operation), ensuring on-going infestations. As seed production is the key to the persistence of *Avena* spp. in farming systems (Medd, 1996a), it is not surprising that wild oats proliferate in the mid-north of South Australia and throughout southern Australia.

7.2 Emergence pattern of *Avena* spp.

The management of wild oats in farming systems can be difficult due to its protracted germination habit. An extended pattern of emergence was confirmed in seed bank studies (Chapter 4) at two sites, as *Avena* spp. emerged over a five month period in

all years (Figures 4.1b, 4.2b and 4.7b). This phenomenon contributes, in part, to the inability of early applied avenacides to prevent wild oat seed production in crops, thus resulting in an increase in seed bank numbers of *Avena* spp. in cropping systems (Medd, 1990; Martin and Felton, 1993). Therefore, the philosophy of extending the timing of in-crop herbicides to counteract the protracted emergence pattern of wild oats appears highly appropriate to prevent seed production.

7.3 Flamprop-*m*-methyl for the control of *Avena* spp.

Several studies were undertaken to determine the effect of timing of flamprop-*m*-methyl application on wild oat seed production (Chapter 6). Field studies conducted in commercial wheat crops determined that the optimum timing of flamprop-*m*-methyl application was at the early elongation stage of wild oats. This resulted in a 97% reduction of seed production when the herbicide was applied at the recommended rate (Table 6.8). Given that seed production can practically be prevented using this technique, and wild oat seed banks decline rapidly under these circumstances (Figures 4.3, 4.4 and 4.8), flamprop-*m*-methyl has the potential to significantly reduce *Avena* spp. seed banks in the wheat phase of crop rotations in southern Australia. Flamprop-*m*-methyl may have a very useful role for minimising wild oat seed production. However, continual use of flamprop-*m*-methyl without the integration of other methods of control, would soon compromise its effectiveness. This was indicated in an experiment reported in Chapter 6 (Table 6.10), where, after successive applications of flamprop-methyl (the parent isomer of flamprop-*m*-methyl), resistant individuals were detected in a field population of *Avena* spp. never previously exposed to flamprop-methyl.

7.4 Frequency of *Avena* species

Apart from determining the incidence of wild oats, the survey identified that two *Avena* species infest cropping fields in the mid-north of South Australia. Seventeen percent of fields contained *A. fatua*, 44% *A. ludoviciana* and 39% comprised both species. The importance of these findings in regards to the management of wild oats are hard to gauge. Medd (1996b) claims there are anecdotal indications that the distribution of wild oat species in Australia is changing, with crop management

possibly driving this change. As this is the first survey of its type where the incidence and distribution of *Avena* species has been documented (in the mid-north of South Australia), it is unable to address the issue of management and its relationship with species frequency. Rather, it provides a base level for assessment of possible changes over future years, both from a species and herbicide resistance perspective.

If weed management practices were causing a shift in the distribution of *A. fatua* and *A. ludoviciana*, it may stem from subtle biological differences between the two species. The survey showed that *A. fatua* and *A. ludoviciana* do not differ in their level of infestation within fields (Table 3.3). This may suggest that each species has similar environmental requirements. In addition, results from the seed bank studies indicate that the rate of seed bank decline of single cohorts of *A. fatua* and *A. ludoviciana* are generally similar. However, differences in seed bank decline were noted between species at various stages throughout the experimental period. Of particular note was the greater rate of decline (in two studies) of *A. fatua* early in the growing season, compared to *A. ludoviciana* (Figures 4.5 and 4.6). Under such circumstances, weed management practices like pre-sowing cultivation and the early application of avenacides would kill a greater proportion of *A. fatua* plants compared to *A. ludoviciana*. If both species were present in a mixed infestation (as found in over a third of fields throughout the mid-north of South Australia), these practices would select for the later germinating *A. ludoviciana*. Conversely, if seedlings were not controlled, *A. fatua* would most likely dominate as its early emergence habit would confer a competitive edge over *A ludoviciana*.

7.5 Seed bank decline of *Avena* spp.

Soil seed bank studies in the field established that seed bank decline for *Avena* spp. followed an exponential pattern over a three year period, with the greatest loss occurring in the first year (56-81%). It was found that *A. fatua* and *A. ludoviciana*, and herbicide susceptible and herbicide resistant populations displayed the same general pattern of seed bank decline. Nevertheless, any differences noted between species and between biotypes is not surprising. The pattern of wild oat germination can fluctuate widely with seasons (Medd, 1996a), both between and within populations (Marshall and Jain, 1970) due to the influence of seed dormancy and the

environment (Wilson and Peters, 1992; Morrison and Friesen, 1996). Seed at different depths may also experience a range of environmental conditions, therefore affecting germinability and possibly the rate of seed bank decline (Figure 4.8). Furthermore, in field situations many *Avena* spp. cohorts are available for recruitment. This may also change the decline pattern compared to that reported in these studies for a single cohort.

Given these considerations, it is clear that predicting the rate of seed bank decline for wild oat populations is a difficult proposition. However, it is important a greater number of *Avena* spp. populations are evaluated over a range of environments so findings from these seed bank studies can be verified. Any large differences in seed bank decline are of considerable relevance for seed dynamics models, as to be effective, these variances need to be taken into account. Also, if differences between species are found, ecological comparisons are necessary so as to develop specific management strategies for each species (Medd *et al.*, 1996).

As seed bank decline rates were found to be generally similar between wild oat populations (irrespective of species or biotype), these findings are useful from a management and extension viewpoint. Extension activities must also focus on the importance of adopting a long term approach to controlling wild oats. While *Avena* spp. seeds banks can decline at fast rates when seed production is prevented, the monitoring of populations is absolutely essential. Even after high losses in year 1, sufficient dormant seeds remain to permit reinfestation for several years.

7.6 Herbicide resistance in *Avena* spp.

The repeated exposure of wild oats to herbicides (particularly ACCase inhibitors) in southern Australia has selected for resistance in many populations. In the mid-north of South Australia the field survey determined that 2.3% of wild oat populations exhibit an agronomically relevant level of resistance to diclofop-methyl (Table 3.4). A low level of resistance was also noted in a quarter of the populations tested. Given the survey was undertaken in 1993, and herbicides remain the preferred method for control of wild oats in southern Australian farming systems, it can be reasonably expected that resistance in *Avena* spp. would have increased (Bourgeois and Morrison, 1997). Farmers must be advised it is far easier to minimise the risk of

development of resistant wild oats, than it is to control them after they develop and infest an area. This therefore requires the integration of effective cultural practices to successfully minimise herbicide resistant wild oats.

7.7 Burning the residues from cereal crops for the control of *Avena* spp.

One of the few non-chemical control techniques that can be utilised for wild oat control in continuous cropping systems is burning the residues from cereal crops. The results from several experiments (Chapter 5) concluded that burning can substantially reduce *Avena* spp. seeds on the soil surface, although the level of control may be highly variable. Of all studies reported in Chapter 5, the greatest seed kill (98%) resulted when the largest quantity of stubble (9.48 t/ha) was burnt (Table 5.5). The extent of control is also dependant on the position of seeds at burning, and the timing and temperature of the burn (Cussans *et al.*, 1987), but from an extension viewpoint it can be stated that seed kill of wild oats generally increases with the quantity of stubble burnt (Table 5.5).

Apart from its use as a weed management practice in southern Australia, crop stubble may be burnt to reduce the amount of residue, so as not to hinder cultivation and seeding implements at crop sowing time. Problems generally arise where large quantities of stubble do not flow through equipment that has little trash clearance between tynes. In addition, when crop seedlings emerge into an environment of heavy stubble, seedling establishment may be reduced. Thus, from a wild oat control, sowing management and crop establishment perspective, burning crop stubble is best carried out when heavy stubble fuel loads are available. Furthermore, stubble burning can stimulate plant emergence of those wild oat seeds that survived the burn, therefore seed banks can be further depleted if these seedlings are controlled. However, potentially overriding these factors is that burning is generally discouraged in southern Australia due to the recognised benefits of stubble retention. But if burning benefits the farming system as a whole, and if used judiciously (eg. on heavy soil types), it remains a viable non-chemical method for the control and prevention of herbicide resistant wild oats in southern Australia.

7.8 Cultural strategies for *Avena* spp. management

In southern Australian farming systems, few distinct cultural options for controlling wild oats are economically attractive or sufficiently effective to warrant significant adoption. Therefore, wild oat management must embrace strategies based on sound agronomic principles which; minimise the rate of development of herbicide resistance in *Avena* spp. and reduce seed bank populations. Techniques such as delaying the date of seeding and strong crop competition are readily adopted because of their simplicity, and given the extended emergence pattern of wild oats, are especially important.

In southern Australia, fields with the heaviest wild oat populations are usually sown last. However, there can be a yield penalty associated with later seeding. Farmers cannot postpone seeding until virtually all wild oats have emerged. Alternatively, crops such as safflower and early maturing barley suffer little yield loss when sown late. Therefore it would seem appropriate to determine the effect of incorporating late sown crops into a rotation and their subsequent impact on wild oat seed bank dynamics.

In regards to crop competition, farmers in southern Australia are becoming more conscious of utilising competitive crops and cultivars, along with the value of increased crop seeding rates for weed suppression. Creating a competitive crop environment is especially important so as to minimise crop yield loss and minimise seed production from late emerging *Avena* spp. plants. Furthermore, wild oat seeds that develop under the crop canopy may be reduced in their viability (Brelsford and Maxwell, 1995).

7.9 Alternative strategies for *Avena* spp. management

Any technique that limits seed production and seed spread will contribute to the long term control of wild oats. Control strategies that have not been mentioned throughout this thesis, but are relevant, include sanitation measures, weed mapping, and in future, the incorporation of transgenic herbicide resistant crops into the rotation.

According to Thill *et al.* (1994) the immigration of wild oats can be prevented by planting clean seed, cleaning harvest and tillage equipment between fields, and

covering grain trucks used to transport grain. Naber *et al.* (1996) found such measures to be vital for the success of an *A. fatua* eradication program in the Netherlands. Preventing the migration of wild oats into previously uninfested areas is especially important considering the seed longevity of wild oats is at least four years (as measured in the seed bank studies). Sanitation techniques are generally under-adopted in southern Australia and should be widely advocated as a basis to IWM for wild oats.

The importance of sanitation, along with weed mapping cannot be disputed. As observed in fields throughout the mid-north of South Australia, *Avena* spp. frequently occur in patches. Therefore weed mapping has particular relevance for wild oats. Weed mapping can be enhanced through the use of global positioning systems and computers (installed in crop harvesters) that accurately map weed distribution patterns in the field (Thill and Mallory-Smith, 1997). By continually monitoring fields for heavy wild oat patches, zone or area management can be adopted if infestations are recognised in certain areas of the field (Thill *et al.*, 1994). Spraying only those patches where wild oats have colonised, reduces herbicide usage and is therefore beneficial from an economic and environmental perspective (Audsley, 1993).

In the near future, transgenic glyphosate and glufosinate resistant canola, and glufosinate resistant lupins will become available to southern Australian farmers (Bowran *et al.*, 1997). Such transgenic crops, provided they are not over-used, will constitute a valuable part of a wild oat (and other weeds) management program.

7.10 Feasibility of control strategies for *Avena* spp. management

Irrespective of the effectiveness of strategies used for wild oat management in farming systems, they must be economically viable to justify adoption. Bioeconomic models which consider the population dynamics of *Avena* spp. can be used to simulate the economic and agronomic feasibility of control measures (Gonzalez-Andujar and Fernandez-Quintanilla, 1993; Jones and Medd, 1997). Management strategies may be tested over a specific time period, in their own right, or in combination with other techniques over different crop rotations. Jones and Medd

(1997) using data from northern New South Wales, analysed herbicide and crop rotational options, and fallow as control methods for wild oats. It was determined that direct reduction of seed production and minimised *Avena* spp. seed bank populations, produce the greatest economic benefit. Most likely this is also the case for southern Australia, however, due to inadequate information on the population dynamics of *A. fatua* and *A. ludoviciana*, it remains to be validated.

7.11 Conclusions

Data gathered from a field survey and experimental studies show unequivocally that an IWM program is essential for short and long term control of wild oats in southern Australian farming systems. *Avena* spp. populations were found to be widely dispersed throughout a major cropping region of southern Australia. Some populations displayed resistance to herbicides, they possessed an extended pattern of emergence and remain viable in the soil for at least four years. These factors, along with their other noted survival mechanisms (early seed shedding ability, high seed production potential, variable seed dormancy mechanisms and strong competitive ability) make the management of wild oats difficult. Therefore a high priority must be placed on preventing wild oat migration into previously uninfested areas. This can only be achieved through the utilisation of sanitation techniques. If wild oats develop into a problem, management must focus on the prevention of new seed production. According to the research reported here, *Avena* spp. seed banks will decline rapidly without fresh seed injection. Two techniques, crop stubble burning and the application of flamprop-*m*-methyl as a late applied post emergent, were shown to be effective in reducing *Avena* spp. seed survival and production. These methods may be utilised as part of an IWM program to manage *Avena* spp. in southern Australia. Components of an IWM system for wild oat management include herbicide rotation, cultural techniques and good agronomic practices. A program which best minimises seed bank populations and does not solely rely on herbicides, will be the most successful for the long term control of wild oats in southern Australian farming systems.

Appendices

Appendix 1 Average monthly rainfall for years when field experiments were conducted at various sites.

	Monthly rainfall (mm)													
	Roseworthy†					Waite‡				Kapunda†			Auburn‡	
	1993	1994	1995	1996	long term	1994	1995	1996	long term	1994	1995	long term	1994	long term
January	49	28	18	66	21	44	19	46	24	13	27	21	2	25
February	7	12	29	29	19	16	33	15	24	9	20	20	12	24
March	12	0	14	18	20	0	17	23	24	0	8	23	0	26
April	3	11	27	20	38	16	57	28	53	1	50	39	4	44
May	21	17	45	5	49	33	65	18	77	17	33	55	19	67
June	45	75	55	72	53	81	75	120	76	95	53	58	141	77
July	38	32	88	86	49	50	153	97	89	36	96	60	39	75
August	40	11	17	81	52	19	31	127	76	3	16	62	25	76
September	64	9	25	72	46	32	50	71	63	22	51	54	44	68
October	89	25	50	26	43	49	27	38	53	34	50	47	46	55
November	20	34	8	12	27	50	13	5	37	57	29	31	86	37
December	24	7	10	16	23	9	11	15	31	5	0	25	9	27
Total	412	261	382	503	440	399	551	603	627	292	433	495	427	601

†The normal growing season extends from April to October.
‡The normal growing season extends from April to November.

Appendix 2 Experimental techniques (laboratory test or pinch test) used to evaluate the viability of *Avena* spp. seeds.

Laboratory test

Avena spp. seeds were placed in containers containing a solution of 0.6% agar and 0.1% thiram (a fungicide), moistened with water and transferred to a refrigerator set at 4°C for a period of seven days for vernalisation. Samples were then placed in a laboratory growth chamber maintained at a 12 hour, 15°C light / 12 hour, 10°C dark regime. Twenty six days later the seeds were evaluated for germination (radicle protrusion). Seeds which had not germinated after this process were dehusked, pricked at the embryo end with a fine dissecting needle and placed in a 9 cm petri dish containing two sheets of Whatman filter paper (No. 1). The seeds were then treated with 5 ml of 2.0 m*M* gibberellic acid and 0.1% thiram (a preliminary study determined that 0.1% thiram had no affect on the efficacy of gibberellic acid), returned to the growth chamber and kept moist. After 23 days the seeds were again evaluated for germination. Seeds which had not germinated after this process were deemed 'dead'. Alternatively, seeds which germinated without the assistance of dehusking, pricking and gibberellic acid application were deemed 'germinable', whilst seeds that germinated with and without assistance were recorded as 'viable'.

Pinch test

Seeds were subjected to a qualitative test in which apparent viability was identified by applying pressure to each seed with the thumb and forefinger. Seeds that contained a hard caryopsis and resisted pressure were recorded as viable.

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