Chapter 1. General introduction and review of literature

Avena spp. (wild oats) continue to be a serious weed of cropping systems in all of the major international grain growing regions. It is a major economic problem in Australia, costing the grain growers an estimated $80 million annually (Medd 1996a). The two main components of this cost are herbicide application costs ($57 million/year) and crop yield losses ($20 million/year) which can be as high as 75% with modest yield losses compounding to bigger proportional losses in gross margins (Wilson 1979a). Yield losses are due to competition for nutrients, moisture and light (Carlson *et al.* 1981).

In northern New South Wales, the region of specific interest for this thesis, a survey of landholders found 86% of respondents considered wild oats an important weed, that the weed was widespread in the region and had an average plant density of 0.54 plants/m^2 (Martin *et al.* 1988). Likewise, Lemerle *et al.* (1996) found wild oats were also widespread in southern New South Wales, with 72% of field sites surveyed being infested with wild oats.

The two wild oat species of importance in cropping systems of New South Wales are *Avena fatua* L. and *A. ludoviciana* Durieu (synonymous with *A. sterilis* ssp. *ludoviciana* (Durieu)) (Harden 1994). This is the nomenclature adopted throughout this thesis unless indicated otherwise. The dominant species in southern grain growing districts of Australia is *A. fatua* (Paterson 1976) whilst *A. ludoviciana* is the dominant species in northern New South Wales and southern Queensland (McNamara 1966; Whalley and Burfitt 1972). There have been no recent surveys to indicate if this distributional pattern has altered. In addition, there can be considerable variation within a species of *Avena* such that classifications can be made according to a specific phenotypic trait (collectively titled 'strain'), their location / general characteristic (collectively titled 'selection') or a sub-population characteristic that results from a specific influence, e.g. herbicide resistance (collectively titled 'biotype'). Physiological and morphological differences have been shown between wild oat plants of the same species and such differences are associated with the location in a specific grain growing region (Thurston 1957; Whalley and Burfitt 1972; Paterson *et al.* 1976a; Millet *et al.* 1982).

In the United Kingdom wild oats have spread and become widely dispersed due to transportation of contaminated grain (Thurston and Phillipson 1976), increased growing of winter cereal crops (Elliott 1972; Cussans 1976) and the introduction of headers (Paterson 1963). For these reasons Thill *et al.* (1994) stressed the importance of sowing clean seed to prevent new infestations or the proliferation of existing infestations. The survey by Martin *et al.* (1988) found that 43% of farmers in northern New South Wales used registered seed and 49% graded seed using a gravity table in an effort to prevent wild oat persistence. Even though the majority of farmers used 'clean' seed, annual population increases are commonplace (Wilson *et al.* 1977; Martin and Felton 1990) despite achieving acceptable levels of control using wild oats with herbicides. The build up of wild oat populations forces farmers to either long fallow land or rotate to other winter or summer crops or pasture (Martin *et al.* 1988). Persistence or population increase could also be affected by factors such as herbicide resistance, seed dormancy, inadequate control by herbicides, seed production, periodicity of emergence and burial in soil. Some of these factors appear to vary according to location, as will be discussed in this literature review.

The emphasis in weed management over past decades has been on improving plant kill to achieve potential maximum yields (Chow and Dryden 1975; Kirkland and O'Sullivan 1984; Anderson and Howat 1990; Pandey and Medd 1990). These short term strategies and associated technologies have failed to contain wild oats in winter cropping rotations in northern New South Wales. For these reasons a thorough understanding of the factors affecting wild oat persistence is necessary to develop a successful integrated weed control strategy for long term management of wild oats, and this forms the focus of this thesis.

After defining the major factor(s) associated with wild oat persistence in Australia from information in the literature, the general objectives of this thesis were to investigate treatments that might reduce populations and provide better long term management of wild oats than the current plant kill tactics. To be commercially successful, any new technology must have acceptable levels of crop phytotoxicity and this was an integral part of the investigations.

1. *Review of literature*

1.1. *Introduction*

Wild oats are annuals that rely solely on seeds to reproduce and spread. Figure 1.1 illustrates the life cycle of wild oats with the various inputs and outputs to the seed bank, and the development, survival and reproduction of various cohorts of seedlings. This review of literature will discuss the factors associated with wild oat persistence, namely biological characteristics of the species and management practices, and examines how they contribute to the life cycle of wild oats.

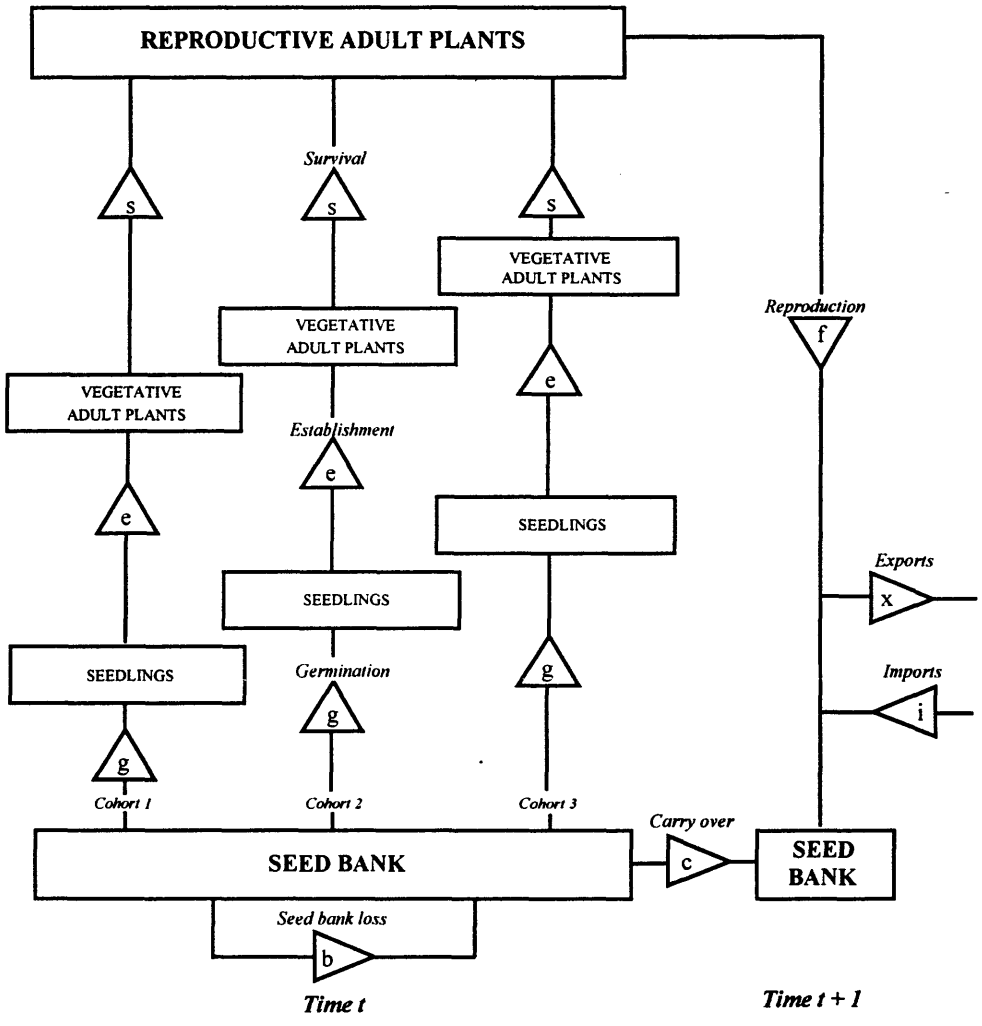

Figure 1.1. Flow chart of the population dynamics of *Avena* spp. showing transitional phases of germination (g), establishment (e), survival (s) to adult plants, reproduction (f), imports (i) and exports (x) of seeds to / from the system, seed bank loss (b) and carry over (c) of seeds to the following season. Adapted from Cousens and Mortimer (1995).

1.2. *Factors affecting the persistence of wild oats*

1.2.1. Cultivation and burial of seed

Information presented in this section reports the effects of cultivation and burial on the loss of seed from the seed bank via seed mortality or emergence, whereas cultivation, as covered in Chapter 1.2.2, primarily emphasises losses in terms of plant kill.

Burial of wild oat seed is inevitable even under no-tillage systems because the hygroscopic awn assists with burial under alternating wet and dry conditions (Wilson 1972). Cultivation will potentially increase the burial depth of seed compared with no-tillage systems.

Burial of seed appears to decrease the amount of seedling emergence, particularly in the first year after cultivation, at least in the United Kingdom (Thurston 1956; Murdoch 1983), Australia (Quail and Carter 1968; Paterson *et al.* 1976b) and the United States (Tingey 1961). Thurston (1961), Banting (1966), Quail and Carter (1968), Wilson (1972), Zorner *et al.* (1984), and Miller and Nalewaja (1990) all indicated rapid loss of viability in seeds located at the soil surface compared with more deeply buried seeds. Seeds exposed to light have increased germination percentages compared with seeds kept in dark conditions (Whittington *et al.* 1970), therefore suggesting that surface seeds will be more rapidly depleted from the seed bank. Whybrew (1964) attributed the greater losses of surface seed to removal by birds. Burning of stubble will also cause some mortality of surface seeds, as discussed in Chapter 1.2.2. Another reason is the high rate of seedling mortality, following relatively small falls of rain, which cause the initiation of germination but the seedlings die because of the rapidly drying conditions (Wilson 1972), which is termed 'fatal' germination (Medd 1987). 'Fatal' germination can also occur for seeds at greater depths and is related to soil type and bulk density of the soil (Egley and Chandler 1983). Smaller wild oat seeds may have less endosperm and so energy reserves might be insufficient to allow them to emerge from normal depths (Medd 1987). A study by Holroyd (1964) showed that wild oat seeds can germinate and emerge from 17 cm below the soil surface. From this study, the largest seedlings were those that emerged from depths between 12 and 15 cm. Nietschke (1997) stated that

dormancy of wild oat seed can be prolonged by the burial of seed. Furthermore, certain pre-emergence herbicides which are normally incorporated to a depth no greater than 5 cm, may not affect the deeply emerging wild oat seedlings (Parker 1963).

The depth of burial will depend on the type of cultivation used. Ploughing in comparison with shallow cultivation will reduce the initial emergence in the first year, but ploughing in following years may bring deeply buried seed back to the surface resulting in greater levels of emergence and a greater population over time (Oliphant 1977; Wilson 1978; Wilson 1981a; Wilson 1985; Medd 1990). Rotary cultivation was shown to increase wild oat seedling emergence in the following spring compared with undisturbed stubble (Wilson and Cussans 1972). In contrast, Martin and Felton (1990) demonstrated no detectable differences after two years in wild oat seed banks following no tillage and chisel ploughing. Any effects arising from choice of cultivation in that study were masked by the overall rapid decline in seed banks.

A study by Quail and Carter (1968) indicated that seed viability and emergence was greater in heavier soils compared with lighter textured soils. No explanation was given for the improved emergence in the heavier soils, but it could possibly have been associated with the cracking nature of these soils, allowing more seedlings to reach the surface and establish successfully.

1.2.2. Fallow management

Fallowing of soil between harvest and sowing is a routine practice of continuous winter cereal cropping. The three forms of fallowing commonly used in Australia are short, long and winter fallowing. A short fallow commences after harvest (e.g. winter crop) and finishes when the next crop (e.g. another winter crop) is sown and is usually no longer than six to eight months, whereas long fallowing continues for at least 16 months and means that one winter crop is foregone before planting in the next autumn. Winter fallowing occurs when changing from a winter crop to a summer crop and involves leaving the soil bare for approximately 12 months. Removal of wild oat plants in all types of fallows is generally achieved by either grazing, cultivation or application of herbicides.

Grazing provides cost effective control if managed correctly, using high stocking rates prior to panicle emergence (Collett pers. comm.). If stock are allowed to graze wild oats with emerged panicles, there is evidence to suggest that mature seed passing through digestive tracts will have very low viability (Thurston 1963; Kirk and Courtney 1972; Blackshaw and Rode 1991).

Cultivation is often practised, particularly if the dual purpose is for seed bed preparation and weed control. The use of cultivation has been discouraged in recent years because of the increased cost of ownership and operation of farm machinery combined with the promotion of the benefits of minimum or no-tillage farming systems (Fellowes *et al.* 1979). Despite this, 81% of farmers surveyed in northern New South Wales in 1985 cultivated soil between three and five times prior to sowing a crop (Martin *et al.* 1988). The same report stated that glyphosate was the most commonly used herbicide for fallow wild oat control. Efficacy of glyphosate for rates between 0.18 and 0.27 kg a.i. (active ingredient)/ha was considered to give excellent control in terms of killing wild oat plants prior to jointing (Fellowes *et al.* 1979). Furthermore, Martin and Felton (1990) and Navarrete and Fernandez-Quintanilla (1996) could not detect any differences in efficacy between tillage and no-tillage (herbicide) fallows, with the latter report stating that both systems almost achieved 100% reduction in seed production. Fernandez-Quintanilla *et al.* (1986) also reported a complete kill of wild oats after pre-planting tillage.

In the United Kingdom, Scragg and Carnegie (1987) reduced wild oat seedlings by 94% after three years using six-monthly cultivations; this is equivalent to a 60.8% annual reduction in wild oat seeds, and thus is somewhat less than 75% recorded in Australia (six month half-life stated by Martin and Felton (1993), Chapter 1.2.3). Furthermore, Thurston (1966) also concluded that fallowing was not an efficient control technique in the United Kingdom because modest declines were experienced in the first year of fallowing and little benefit was obtained with an additional winter fallow.

Timing of cultivation may also be important because Wilson and Cussans (1972), Zorner *et al.* (1984) and Nietschke (1996) emphasised the need for later cultivation to kill greater

numbers of emerged seedlings. Zorner *et al.* (1984) recommended the use of very shallow cultivation as late as possible, whilst Wilson and Cussans (1972) recorded more than twice as many wild oat plants after early autumn cultivations compared with leaving soil undisturbed until late autumn, over six sites and various soil types.

Fallow weed control practices, as discussed above, are much more effective than in-crop weed control (Navarrete and Fernandez-Quintanilla 1990; Martin 1992) and are therefore likely to reduce the persistence of wild oats. Consequently, McNamara (1972) and Martin (1992) recommend the use of winter fallows to obtain maximum control of seed production. Navarrete and Fernandez-Quintanilla (1996) concluded that a higher proportion (fourfold) of seeds germinate from paddocks cropped with barley compared with fallow ground, a likely interaction resulting from crop residues (as explained in Chapter 1.2.6).

Burning stubble in fallows had the effect of reducing wild oat seed banks by 32% (Wilson and Cussans 1975). The authors also concluded that stubble burning combined with delayed cultivation reduced seed numbers by 73%. Total seed kill from stubble burning is unlikely since temperatures of 105°C for 15 minutes is required (Hopkins 1936), but these conditions are unlikely to occur even on the soil surface. Burning also stimulated surface seed germination by reducing dormancy of survivors (Whybrew 1964). Stubble burning is primarily used in Australia to prevent yellow leaf spot disease and is only used sparingly by farmers in northern New South Wales (Martin *et al.* 1988). Thin crops resulting from lower rainfall or drought, the desire to prevent soil erosion and the need for increasing soil organic matter are reasons why stubble burning may not be practised.

1.2.3. Crop / pasture rotations

The reductions in wild oat populations after one and two years in a sorghum / winter fallow in northern New South Wales were 96.6 and 99.8% (Philpotts 1975). An additional winter fallow had no significant benefit over the two year fallow system. Similar declines in wild oat seed banks were found by Wilson *et al.* (1977) in south eastern Queensland, after two or three summer crops. Similarly, Martin and Felton (1993) found wild oat seed banks declined rapidly under a sorghum rotation with wheat in northern New South Wales. The rotation

involved was wheat - winter fallow - sorghum - winter fallow - wheat crop cycle and resulted in an average reduction in viable wild oat seeds in the seed bank of 93%. From these results, wild oat seed banks were estimated to have a half-life of six months.

A sorghum rotation was found to be the most popular form of cultural control specifically aimed at wild oats in northern New South Wales with 51% of respondents from a survey using this technique (Martin *et al.* 1988). Furthermore, the survey also found that 47% of respondents used lucerne crops / pastures to achieve cultural control. McNamara (1972) and Martin (1992) also recommend the practice of rotating wheat with a pasture phase to ensure reductions in wild oat seed banks and the reduction of herbicides applied. An investigation using gross margin analysis by Wilson (1979a) found that rotating winter and summer crops provided adequate control of wild oats without reducing gross margins.

The option of rotating with summer growing crops is limited to the northern grain belt. Due to lack of summer rainfall, southern rain-fed grain regions are generally restricted to either an alternative winter crop, long pasture phases or long fallowing.

In the United Kingdom, Wilson and Phipps (1985) compared several rotational strategies: continuous wheat or barley combined with standard herbicide application; having a three or six year period of grass pasture that was mowed when necessary; and barley cut for silage for three years. Although the first two strategies did not result in satisfactory long term declines in wild oat populations, silage production from barley crops depleted wild oat populations to negligible levels after four years. Changing agronomic practices, such as switching from winter wheat crops to spring barley combined with conventional herbicide use or growing spring beans without the use of herbicides have led to noticeable reductions in wild oats in the United Kingdom (Jarvis and Clapp 1981). From another study in the United Kingdom, spring barley grown for four successive years produced a larger drop in numbers of emerging wild oats after the four year period compared with winter barley (Scragg and Carnegie 1987). This study also concluded that the adoption of a grass ley for two years, with the aim of exhausting wild oat seed reserves, actually preserved the seed and more seedlings emerged after the soil was cultivated. A similar effect was reported by Thurston (1982) after several years of pasture, with significant declines in the seed bank after the first year but slow reductions

thereafter. The lack of soil disturbance is a possible reason for wild oat seed survival / persistence in this situation, particularly with deeply buried seed (Chapter 1.2.1).

The remaining literature highlighting crop rotations for cultural control of wild oats originates from Spain. Fernandez-Quintanilla *et al.* (1984) found an 80% annual increase in wild oat seed bank with continuous winter wheat cropping, without using herbicides. However, the growing of spring barley without herbicides resulted in a 10% annual reduction, but more significantly, the use of summer crops led to at least a 57% annual decline in soil seed reserves. Furthermore, results of experiments reported by Navarrete and Fernandez-Quintanilla (1990) found that a sunflower - vetch - winter barley - sunflower rotation reduced wild oat seed banks by 96% after three years. In the same report, spring barley - fallow - winter barley - fallow rotations with either no-tillage or conventional wild oat control by tillage in the fallow phase gave similar reductions in seed banks.

1.2.4. In-crop herbicide applications

The primary aim of in-crop herbicide use is to suppress the competitive effects of wild oats so that maximum crop yields are achieved. A number of reports (Winfield and Caldicott 1975; Anderson and Howat 1990; Koscelny and Peeper 1997) have demonstrated yield benefits following the annual application of post-emergence herbicides but have not considered the long term effects on wild oat populations. Jutsum and Bryan (1992) and Medd (1997) have emphasised the persistence of wild oats despite the latest efforts with herbicide technology.

It is unrealistic to expect to achieve 100% control of wild oats, either in the context of plant kill or reproduction (Brewster and Spinney 1989; Jensen 1990) and this has been the experience with tri-allate (Paterson 1967; Holroyd and Bailey 1970; Proctor and Armsby 1974; Fernandez-Quintanilla *et al.* 1987), flufenprop-methyl (Olsen and Nalewaja 1977), clodinafop (Blackshaw and Harker 1996), difenzoquat (Proctor and Armsby 1974; Winfield and Caldicott 1975; Miller *et al.* 1978; Fernandez-Quintanilla *et al.* 1987; Navarrete and Fernandez-Quintanilla 1996), imazamethabenz (Navarrete and Fernandez-Quintanilla 1996; Koscelny and Peeper 1997), tralkoxydim (Harker and Blackshaw 1991), barban (Friesen 1967; Proctor and Armsby 1974; Friesen *et al.* 1976), chlorfenprop-methyl (Holroyd and Bailey 1970), experimental herbicide

HOE 23408 (Friesen *et al.* 1976), flamprop-isopropyl (Fernandez-Quintanilla *et al.* 1987) and fenoxaprop-ethyl (Anderson and Howat 1990; Koscelny and Peeper 1997). Other longer term studies (at least three years) have similarly shown incomplete control and that herbicides fail to contain wild oat populations, notably flamprop-methyl (Martin and Felton 1990), benzoylprop-ethyl (Breslin 1974; Jarvis and Clapp 1981), flamprop-isopropyl (Jarvis and Clapp 1981; Fernandez-Quintanilla *et al.* 1987), tri-allate (Wilson *et al.* 1977; Fernandez-Quintanilla *et al.* 1987; Martin and Felton 1990), difenzoquat (Jarvis and Clapp 1981; Wilson and Phipps 1985; Fernandez-Quintanilla *et al.* 1987; Navarrete and Fernandez-Quintanilla 1996) and barban (Wilson *et al.* 1977; Wilson and Phipps 1985).

Factors which contribute to the incomplete control of wild oats include survival of some plants due to 'misses' or 'escapes' (Medd 1992a), possibly because of unfavourable spraying conditions (Jensen 1990) which leads to seed production and perpetuation of the seed bank (Fay 1975). Unfavourable environmental conditions such as moisture stress, have been shown to reduce the absorption and translocation of fenoxaprop-ethyl in *A. fatua* (Xie *et al.* 1996), resulting in reduced efficacy (Wilcox *et al.* 1987). Fernandez-Quintanilla *et al.* (1987) demonstrated that the type of herbicide is a critical factor in determining efficacy with flamprop-isopropyl, causing low plant mortality but more effectively reducing seed production, whereas tri-allate caused higher plant mortality with little influence on seed production. These findings can be explained in terms of the time of application in relation to wild oat growth stages, which has also been shown to critically influence efficacy by Friesen (1967), Holroyd and Bailey (1970), Friesen *et al.* (1976) and Kirkland and Shafer (1982). Late germinating wild oats are unaffected by early applications of herbicides, whereas later applications are likely to be tolerated by more advanced plants. Reducing herbicide rate is another factor that can lower efficacy (Friesen *et al.* 1976; Anderson and Howat 1990).

1.2.5. Herbicide resistance

The definition of herbicide resistance is the inherited ability of a plant to survive a rate of herbicide that would normally kill the same species and cannot be explained by other factors such as unfavourable spraying conditions or lack of herbicide contact due to poor application (Maxwell and Mortimer 1994). Herbicide resistance usually develops after repeated

applications of highly efficacious herbicides because plant populations alter their genetic composition in response to the selection pressure of herbicides (Maxwell and Mortimer 1994; Jasieniuk *et al.* 1996).

Currently, the majority of wild oat herbicides are in herbicide Group A, a group classified as having a high risk for developing herbicide resistance in plants. This group is split into sub-groups called 'fops' and 'dims'. The 'fops', a sub-group of herbicides known as aryloxyphenoxypropionates, include herbicides such as fenoxaprop-p-ethyl, diclofop-methyl, clodinafop, haloxyfop and fluazifop. The sub-group know as cyclohexanedione ('dims') contain herbicides tralkoxydim and sethoxydim.

In 1985 wild oats from Western Australia suspected of having diclofop-methyl herbicide resistance was confirmed by Boutsalis *et al.* (1990) and Piper (1990). Diclofop-methyl was applied to these wild oats, and although panicles produced were less dense than untreated plants, the density of panicles was commercially unacceptable. Four years later, wild oats from South Australia were shown to have resistance to haloxyfop-methyl (Mansooji *et al.* 1990). These populations had no previous exposure to haloxyfop-methyl, but paddock histories indicate six applications of other 'fop' herbicides. In summary, there are approximately 25 cases of 'fop' herbicide resistance in Australia for *A. fatua* in all mainland grain growing states except Queensland (Davis 1992). Davis (1992) and Mansooji *et al.* (1992) have also noted 'fop' and 'dim' resistance in *A. sterilis* ssp. *ludoviciana* in South Australia. The survival rate of herbicide resistant plants depends on herbicide rate and type of herbicide used and can be as high a 100% with recommended dose rates (Joseph *et al.* 1990; Mansooji *et al.* 1992). The reproductive capability of herbicide resistant wild oats has never been measured after herbicide application, although Heap *et al.* (1993) in Canada, measured a modest drop in shoot dry weight (27%) after application of eight times the recommended dose rate of sethoxydim.

Surviving plants, generally resistant to herbicides, will replenish the soil with 'herbicide resistant' seed and susceptible plants are not likely to survive to return 'susceptible' seed to the soil. Consequently, the practice of applying a herbicide to which the wild oats are resistant, will increase the proportion of resistant plants in the population.

Most cases of herbicide resistance are likely to occur under continuous cropping situations, with repeated applications of herbicide from the same group, usually in conjunction with minimal cultivation (Leys and Dellow 1991). Therefore, Leys and Dellow (1991), Davis (1992), Jutsum and Bryan (1992) and Nietschke *et al.* (1996) have recommended that alternatives to the standard heavy reliance on post-emergence herbicide tactics are required to avoid herbicide resistance. An integrated weed management approach is required, using options such as crop rotations, cultivation (Nietschke *et al.* 1996) and herbicides with different chemical activity (Powles and Holtum 1990; Powles and Howat 1990; Jutsum and Bryan 1992). Nietschke *et al.* (1996) recognised the use of flamprop-methyl, although an old herbicide, as a preferred post-emergence option because it is within herbicide Group K and will have activity against herbicide Group A resistant wild oats. Upon discovery of any herbicide resistant wild oats, attempts must be made to prevent seed production to limit the perpetuation of the problem (Leys and Dellow 1991).

1.2.6. Biological agents and allelopathic interactions

Few studies have examined the possible influence of biological agents including nematodes, aphids, fungi, bacteria, viruses on wild oats. Medd and Ridings (1989) suggested the use of biological agents to achieve population control of wild oats, but recognise that the chance of successful biological control without consistent application of the pathogen is low.

Nematodes have been reported to cause some damage to wild oats, although the level of injury is not sufficient to have any impact on plant or population size (Franklin 1970). The cereal cyst nematode (*Heterodera avenae*) has been noted to cause moderate symptoms on wild oats in Victoria (Meagher and Brown 1972), but its potential as a biological agent is questionable due to variable impacts and possible damage to cereal crops. A review of the subject by Thurston and Cussans (1976) found no successful cases of aphid damage to wild oats, but they noted that aphids could act as a vector for some of the seven viruses identified as infecting wild oats, however many are likely to cause crop damage.

Fungi have the most potential as biological control agents. There are two groups of seed-borne fungi with this potential: fungi that infect the seed in soil and those that infect seed whilst on the parent plant (Medd 1985). Kiewnick (1963) screened 36 fungi for pathogenicity to wild oat seeds and found the highest death rate of seed was 32%, caused by *Stemphylium consortiale*. This fungus, along with the next four most effective fungi, also cause diseases to cereals. *Pyrenophora avenae*, a seed or soil inoculated fungus was investigated by Wilson and Hall (1987) and caused significant seed mortality. It could be promoted for use in wheat and barley without unacceptable crop injury, but it could not be used in cultivated oat crops. Medd and Campbell (1996) summarised the effects of *Pyrenophora semeniperda* on wild oats and wheat. The fungus caused significantly more infected seed, reduced emergence and vigour of wheat compared with wild oats. Consequently Medd and Campbell (1996) could see no reason to recommended it for selective control in wheat. Two isolates of the fungal pathogen, *Drechslera avenacea*, were selected by Hetherington *et al.* (1998) as potential bioherbicides because of their ability to cause severe symptoms on wild oats but not on wheat.

Persistence of wild oats in Australia may be affected by the allelopathic effects of residues of a wheat crop (Purvis and Jessop 1985; Purvis *et al.* 1985; Purvis 1990a). Purvis *et al.* (1985) found increased germination, growth rates and seed production of wild oats, with up to 10 fold increase in dry weight of wild oats and 42 fold increase in seed production in the presence of wheat residues. In regions where summer cropping is feasible, Purvis (1990b) reported that residues of mung bean or sorghum crops caused a 94 and 71% reduction respectively, in the emergence of wild oats, compared with a clean fallow (99% emergence of seeds). Results from the same study indicate that sorghum residues delayed and compressed the emergence pattern of wild oats, resulting in more synchronised wild oat growth stages. This should improve herbicide control as most herbicides have specific optimum wild oat growth stages for effective control (Friesen 1967; Holroyd *et al.* 1976; Kirkland and Ashford 1976; Paterson 1977) because a lower proportion of plants should fall outside the optimum growth stage. A delayed emergence of wild oats within a crop will result in less competitive weeds, they are likely to achieve lower biomass and seed production compared with earlier emerging wild oats (Peters 1984).

The degree of allelopathy depends on the quantity of stubble; Purvis and Jones (1990) demonstrated that a threefold increase in sorghum and sunflower stubble quantity produced a twofold increase in phytotoxicity. The same report concluded that a soil type with a sand / silt / clay content of 58, 5 and 36% respectively produced the strongest effects and allelopathy was increased if the stubble was incorporated. Furthermore, Purvis (1990c) found that unweathered stubble has greater phytotoxicity than partly decomposed stubble. The reports quoted in this paragraph investigated the effects of stubble on wheat but may apply for wild oats.

1.2.7. Dormancy and longevity

Seed dormancy is the condition referring to the temporary suspension of germination when given favourable conditions for germination (Simpson 1990). More precisely, dormancy can be categorised into either primary (innate) or secondary (induced) dormancy. Primary dormancy is initiated in the early stages of development of the seed and secondary dormancy is the re-introduction of dormancy after primary dormancy has been completely, or almost completely terminated (Simpson 1990) and is caused by certain environmental conditions (Roberts 1972). Longevity of seeds in the soil would be extended by high levels of either or both primary and secondary dormancy. Persistence of wild oat seed banks would be mainly caused by secondary dormancy.

Environmental factors that can affect wild oat seed dormancy in soil include genetic variability (Whittington *et al.* 1970; Naylor and Jana 1976; Paterson *et al.* 1976b; Medd 1985; Wilson 1985; Peters 1991; Wilson and Peters 1992) and light (Whittington *et al.* 1970). Moisture stress (Sexsmith 1969; Peters 1982; Sawhney and Naylor 1982) or high temperatures (Sexsmith 1969; Sawhney and Naylor 1979; Peters 1982) during seed development will reduce seed dormancy. Low or high soil temperatures (Whittington *et al.* 1970; Paterson *et al.* 1976b), small seeds (Sharma *et al.* 1977), particularly secondary seed (Thurston 1961; Quail and Carter 1969; Wilson and Peters 1992), higher soil clay content (Quail and Carter 1968) and seed coat (Whittington *et al.* 1970; Medd 1985) due to the thickness of the lignified cells on the lemma and palea (husk) (Black 1959; Morrison and Dushnicky 1982) are factors that will prolong dormancy. Emergence patterns can also differ

among species because *A. fatua* generally germinates at higher temperatures than *A. ludoviciana* with a trend for primary seed to germinate earlier than secondary seed (Quail and Carter 1968). The winter emergence of *A. ludoviciana* compared with early season (autumn) emergence of *A. fatua* are likely to be associated with these temperature requirements. In Australia, Paterson *et al.* (1976b) found that temperatures between 11 and 23°C were optimal for germination of wild oat (*A. fatua*) seeds, with temperatures outside this range causing reduced emergence. A similar effect was reported in Canada by Friesen and Shebeski (1961) for temperatures in the range 15.5 to 21.1°C and no germination was recorded at 4.4°C.

In Australia, Martin and Felton (1993) concluded that wild oats have minimal levels of dormancy because the half-life of seed in the soil was estimated to be six months. This is in agreement with remarks from Quail and Carter (1968), McNamara (1972) and Medd (1990) which indicate the loss of viable seed each year is approximately 90%. Low levels of dormancy were found in seed from Alaska, since less than one percent of seed were viable after 3.7 years (Conn 1990). Seed from Syria under a grazed pastures system carried over to the following year at a rate of five percent (Russi *et al.* 1992). Lack of persistence in seed banks was demonstrated by Wilson (1981a), with less than one percent of seed present in the soil after two years (Wilson 1978). However, there is also evidence that wild oats persist because of seed dormancy in the United States (Kommedahl *et al.* 1958; Miller and Nalewaja 1990), United Kingdom (Thurston 1956; Scragg and Carnegie 1987) and particularly Canada (Banting 1961; Simpson 1965; Banting 1966; Sexsmith 1967; Adkins *et al.* 1984; Adkins *et al.* 1987; Adkins 1990). Therefore, the highest reported degrees of dormancy (likely to be induced dormancy) emanate from Canada, mixed evidence for dormancy in the United Kingdom and the least dormancy appears to exists in Australia. The literature suggests that the half-life of wild oat seed in soil seed banks from most countries is fairly short, but that the half-life in Australia seems to be the least of all countries.

Based on this information, wild oat seed dormancy does not seem to be a major cause of longevity and persistence in Australia. Considerable effort has been devoted to manipulating the dormancy of seed in the soil in the northern hemisphere in an effort to enhance germination and provide more synchronised germination. Both these events would allow for greater plant deaths from post-emergence control techniques. Thurston (1961) also attributed

difficulties with breaking of dormancy in soil to the hard seed coat and the range of depths at which wild oats seeds are located. Despite this, dormancy was successfully reduced by various methods including damaging the seed coat or husk (Naylor and Christie 1956; Foley 1987), nitrogenous fertilisers (Sexsmith and Pittman 1963; Watkins 1966; Chancellor *et al.* 1975; Fay 1975; Cairns and de Villiers 1986), potassium (Fay 1975) or sodium azide (Fay and Gorecki 1978; Upadhyaya *et al.* 1983), gibberellic acid (Simpson and Naylor 1962), and ethephon (Saini *et al.* 1985). Notwithstanding these successes, Medd (1985) concluded that the majority of these treatments would be uneconomical and Simpson (1992) stated that genetic heterogeneity and the many factors that cause wild oat dormancy are reasons why control of dormancy will be difficult.

1.2.8. Seed production

Annual plants such as wild oats rely on seeds for reproduction and dispersal (Medd 1996b). Peters *et al.* (1975), Medd (1992a) and Matthews *et al.* (1994) have indicated that surviving plants are capable of producing significant numbers of seeds and Medd (1997) demonstrated that wild oats are capable of producing between 100 and 3,000 seeds/m^2 after standard herbicide applications. Cultural control such as late sowing can be highly effective for reducing wild oat populations in crops, but Selman (1968) noted that the remaining plants produced sufficient seed to perpetuate the wild oat populations. Medd (1997) reported that wild oat seed production for densities between 20 and 100 plants/m^2 ranged between 1,000 and 10,000 seeds/m^2 in crops not treated with herbicides whereas it ranged between 30 and 1,000 seed/m^2 for herbicide treated crops where wild oat densities were between 2 and 20 plants/m^2. Some factors that affect seed production are crop competition (Thurston 1956; Nalewaja 1977) and genetic diversity (Thurston 1961; Quail and Carter 1969; Sexsmith 1969; Nalewaja 1977). These factors and others will be investigated in more detail in Chapter 1.3.

Several reports suggest it is likely that in-crop wild oat seed production in Australia is the main mechanism for maintaining seed bank levels / persistence (Medd and Ridings 1989; Madin *et al.* 1993; Mansooji 1993; Matthews *et al.* 1994; Medd 1997) but have not measured long term seed production and the consequent effects on persistence. This conclusion was also reached by other overseas researchers (Peters *et al.* 1975; Wilson 1978; Simpson 1992).

Others (Elliott 1972; Wilson 1972; Taylorson 1987) have attributed wild oat persistence to both seed dormancy and seed production and Wilson (1972) realised the futility of attempting to control seed persistence in soil to achieve a rapid decline in seed banks.

Information from the literature has shown that many of the transitional phases of the wild oat life cycle (Figure 1.1) do not contribute substantially to persistence. The persistence of wild oats can be seen as the continual carry over of or increase in the seed bank from one season to the next, whether it be by 'old' or recently shed seed. General findings, from Australian research, include low levels of seed dormancy (Chapter 1.2.7) and a relatively small proportion of seed carry over (of 'old' seed) as a likely consequence of high germination percentages. Secondly, establishment and survival is generally low because of effective fallow or in-crop herbicides (Chapters 1.2.2 and 1.2.4, respectively), although in-crop herbicides usually allow a small proportion of survivors. There is no literature that has shown that persistence is associated with the continual import of new wild oat seed into the system as distinct from that produced *in situ*. Therefore, the most likely avenue for replenishment of the seed bank is via the reproductive phase of the plant (seed production). This is likely to occur from survivors, or new recruits which emerge after in-crop herbicide application. From this information it can be hypothesised that wild oat persistence is due more to seed bank replenishment from seed production than to carry over of viable seed reserves in the seed bank, although persistence because of seed dormancy is obviously important.

1.3. *Factors affecting the seed production of wild oats*

After growing monoculture wheat for four successive seasons, Fernandez-Quintanilla *et al.* (1984) recorded seed production of between 2,900 and 9,300 seeds/m^2, the variation reflecting seasonal climatic influences as well as variable plant populations. The maximum corresponds closely to the greatest seed production of 10,000 seeds/m^2 indicated by Medd (1997), but is far short of the 28,000 seeds/m^2 assumed by Martin (1992). The following sections review the factors which contribute to the variation in wild oat seed production and practices that can be used to manipulate or regulate seed production.

1.3.1. Variation amongst ecotypes, selections and species

Among the few studies which have examined differences in reproduction between genotypes, Marshall and Jain (1967) found that *A. fatua* produced less spikelets/plant compared with *A. barbata*. Roebuck and Field (1978) detected differences between *A. fatua* and *A. ludoviciana* such that, when left untreated, *A. fatua* in winter wheat or spring barley had a steady or declining panicle output each successive season whereas *A. ludoviciana* increased spikelet production each year, particularly in winter wheat. These results are supported by findings from Thurston (1957), who demonstrated that *A. ludoviciana* generally produced more panicles per plant than *A. fatua*. Furthermore, Thurston (1957) detected differences in panicles/plant (panicle production) between selections of *A. fatua* or *A. ludoviciana*.

Physiological response to vernalisation (cool temperature requirement) of *A. fatua*, measured by photoperiod, was 16 days less for northern selections compared with southern selections from Western Australia, grown under uniform conditions (Paterson *et al.* 1976a). Whalley and Burfitt (1972) also measured the effects of vernalising seed from New South Wales and southern Queensland and found that *A. fatua* did not have a vernalisation requirement whilst a selection of *A. ludoviciana* responded to vernalisation by producing panicles in less time. Although neither study measured total seed production or other closely related reproductive components, they demonstrated that there is sufficient genetic variability to produce seeds quickly once particular environmental conditions arise.

There is also some evidence that genotypic variation can affect herbicide efficacy in relation to seed production. Rydrych and Seely (1964) found that selections of *A. fatua*, having grey glabrous lemmas and low yields, were more tolerant than seeds with darker coloured lemmas to isopropyl *N*-phenylcarbamate (IPC). Likewise for *A. ludoviciana*, Watkins (1970) stated that plants with grey or brown coloured florets were more tolerant of barban. Paterson (1977) found more than a twofold difference in seed production between three selections of wild oats from northern, central and southern grain growing districts of Western Australia. When treated with a range of herbicides, however, flamprop-methyl was less prone to sub species specificity than difenzoquat or barban.

1.3.2. Time of wild oat emergence

Several studies have found that wild oat plants emerging early in the life of a crop produce more seed or panicles than plants which emerge later in the season (e.g. late winter / spring) (Pfeiffer *et al.* 1960; Wilson and Cussans 1978; Peters 1984; Cousens *et al.* 1992). According to Fernandez-Quintanilla *et al.* (1986) there is a strong negative exponential relationship between time of emergence and fecundity, with fecundity decreasing with later emergence. Decreased fecundity from late emergence can be due to a reduction in panicles or tillers per plant or unit area (Chancellor and Peters 1972; Wilson 1981b; Peters and Wilson 1983; Peters 1984), higher mortality rates (Chancellor and Peters 1972; Peters and Wilson 1983; Peters 1984; Fernandez-Quintanilla *et al.* 1986), smaller panicles (Chancellor and Peters 1972), or less plant biomass (Peters and Wilson 1983; Cousens *et al.* 1992). Inter-specific competition from the crop is a major factor affecting seed production and Martin and Field (1988) found that when wheat and wild oat emerge concurrently they have similar competitive ability. However, wild oats that were sown three to six weeks later than wheat were dwarfed due to root competition, and to a lesser extent shoot competition, and prevented wild oat seed production.

As much as 99% of the total wild oat seed produced originated from plants that emerged no later than the 2.5 crop leaf stage (Peters 1984). In a similar study over two years, Peters and Wilson (1983) reported that 97 and 89% of total wild oat seed was produced by plants emerging before the crop two leaf stage, over two consecutive years. Moreover, Chancellor and Peters (1972) found that the earliest emergence cohort contained plants with the highest fecundity but the highest proportion of seed produced was generally produced by the second or third cohorts because of the greater number of emerged seedlings.

Wild oats can emerge over a protracted period of several weeks. Chancellor and Peters (1972) demonstrated that the period of emergence ranged from 30 to 85 days after sowing crops over twelve sites. Plants which emerge after in-crop treatment with herbicides are therefore likely to contribute disproportionately to seed production as outlined in Chapter 1.2.4. Conversely, Peters and Wilson (1983) showed that between 0 and 59% (average 16% for 32 sites over two years) of wild oat seedlings can emerge before planting and can be effectively controlled with

non-selective herbicides such as glyphosate, as discussed in Chapter 1.2.2. Therefore, these plants do not contribute to seed production, even though they would have the highest potential fecundity.

1.3.3. Competition from crops or other plants

Wild oats are highly competitive for soil nitrogen and at low densities appear to utilise it more efficiently than wheat crops, resulting in more panicles/m^2 (Carlson and Hill 1985). To increase wheat densities so the proportion of wild oat plants in the overall population is small, forms a logical approach that may contribute to the utilisation of more available soil nitrogen by the crop. As a monoculture, wild oats can produce large numbers of seeds (200 seeds/panicle) but with inter-specific competition from a crop, seed production is appreciably lower (10 seeds/panicle) (Thurston 1956; Peters 1985). Thus seed production can be reduced significantly by increasing crop densities (McNamara 1972; Radford *et al.* 1980; Martin *et al.* 1987). Furthermore, McNamara (1972) stated that wild oats may halve seed production if wheat seeding rate is increased from 22 to 44 kg/ha. Evans *et al.* (1991) also demonstrated a decline in wild oat seed production from 4,035 to 1,270 seed/m^2 with an increase in barley density from 135 to 415 plants/m^2.

Spatial arrangement has also been found by Regnier and Bakelana (1995) to affect seed production. A square planting pattern was found to be marginally better than rectangular patterns, causing lower leaf area, tiller numbers and total shoots per plant.

In the UK Thurston (1956 and 1962) suggested that winter cereals are preferred to the later sown spring cereals because they are more competitive against wild oats.

Barley has been shown to be more competitive than wheat against wild oats (Wilson 1979b; Evans *et al.* 1991). Wilson (1979b) showed that the reduction in spikelet production in wheat using a range of herbicides was 70% compared with > 90% in barley relative to untreated areas. Moreover, the choice of crop cultivar can also make significant improvements to competitive ability of crops as shown by Lemerle and Cousens (1992). These previous reports did not consider the allelopathic interaction of crop residues on wild oats. Purvis *et al.*

(1985) has shown that wheat residues stimulate germination and improve the growth of wild oats, such allelopathic interactions are explained in more detail in Chapter 1.2.6.

Nitrogenous fertilisers can increase panicle numbers and seed yield of wild oats grown with barley under controlled conditions (McBeath *et al.* 1970). This effect was confirmed in wheat crops by Sexsmith and Russel (1963), when nitrogenous fertilisers increased wild oat panicle production, plant height and seed production. The addition of nitrogenous fertilisers to wild oats in field conditions without inter-specific competition also increased seed production (Thurston 1956). Timing of nitrogen application can also have an effect on the reproductive potential of wild oats since late applications of nitrogen by Watkins (1971) resulted in increased numbers of wild oat panicles compared with early applications.

1.3.4. In-crop herbicide applications

The use of in-crop herbicide treatments may result in variable levels of seed production. For example, applications of benzoylprop-methyl at rates of 1.12 and 1.25 kg a.i./ha, applied to wild oats at tillering, reduced seed production by 85 to 99% respectively in one season compared with untreated areas (Breslin 1974). In contrast, Chow and Dryden (1975) applied three rates (1.1, 1.65 and 2.2 kg a.i./ha) of benzoylprop-methyl and recorded between 41 and 48% reductions in seed production, regardless of times of application between 1.5 and 5 leaf / early tillering stages whereas difenzoquat applied at rates of 0.7 to 1.0 kg a.i./ha when wild oats were between the two leaf and early tillering stage, gave erratic control. Variable results are also evident from the work of Wilson (1979b), showing approximately 60% reduction in seed production, whereas Winfield and Caldicott (1975) obtained between 86 and 100% reduction in wild oat spikelets, whilst Paterson (1977) reported a 14% decline in spikelets per plant, and flamprop-methyl applied at either 0.4 (Paterson 1977) or 0.45 kg a.i./ha (Wilson 1979b) to early tillering wild oats both resulted in approximately 60% reductions in spikelets.

Although reductions (relative to untreated plants) in reproductive capability of wild oats can occasionally be high from one treatment, seasonal or site averages of seed production should better represent the true effect of in-crop treatments. Wilson and Cussans (1978) showed that the average seed production from six herbicide treatments replicated over six sites was about

2,500 seeds/m^2. Similarly, Wilson (1979b) found that most combinations of four herbicides, at two dose rates over three years and a range of wild oat growth stages resulted in spikelet production of between 500 and 1,500 spikelets/m^2. Although the data in the previous two studies could be greatly affected by variable wild oat plant densities, the consistently large number of seeds produced per m^2 is evidence that continuous use of herbicides will result in large inputs of seed into the seed bank.

When applied near the recommended growth stage for wild oats (for crop yield conservation or reduction of wild oat competition), barban (0.35 kg a.i./ha) significantly reduced seed production by 91% (Wilson *et al.* 1974), 77% (Reeves *et al.* 1973) and 69% (Wilson and Cussans 1978), but did not have any significant impact on spikelets produced per plant when half the rate was used (Paterson 1977). Wille *et al.* (1998) found that imazamethabenz applied at rates greater than 0.26 kg a.i./ha to wild oat densities less than 190 plants/m^2 did not result in wild oat seed production above the initial population density, but as wild oat densities increased from 8 to 1,100 plants/m^2, wild oat seed production increased from 0 to 2,810 seeds/m^2 using imazamethabenz at 0.53 kg a.i./ha. Application timing has also been identified as a factor that affects herbicide efficacy for wild oat panicle production. Madin and Martin (1990) demonstrated that applications of tralkoxydim (150 g a.i./ha) to wild oats at Zadoks Decimal Code (DC) = 24 (early / mid-tillering) (Zadoks *et al.* 1974) produced more panicles/m^2 than if the same treatment was applied at Zadoks DC = 21 (early tillering).

Plants suffering moisture stress at the time of herbicide application regrew more when relieved from stress than did plants sprayed under less moisture stressed conditions (Wilcox *et al.* 1987). From the same study, it was concluded that certain herbicides, for example flamprop-methyl, were less affected by moisture stress than diclofop-methyl. Peters (1982) found that moisture stress was a contributing factor to lower seed production of unsprayed wild oats relative to unstressed plants.

Piper (1990) applied a range of herbicides to a biotype of wild oats known to be resistant to diclofop-methyl and whereas panicle production was 319 panicles/m^2 after treatment with diclofop-methyl, no panicles emerged following treatment with tralkoxydim.

1.4. *Regulating seed production and seed rain*

Because of the seed shedding characteristic of wild oats there are limited options available for preventing the return of seed to the soil, but some possibilities are reviewed, along with literature dealing with the prevention of seed production. Biological control could be used to prevent seed production, but at best can be utilised for seed or seedling infection to kill seed in the soil or to reduce plant vigour as discussed in detail in Chapter 1.2.6.

1.4.1. Mechanical seed collection

Seed collection of species such as *Lolium rigidum* Gaudin (annual ryegrass) is feasible because most seed does not shed from the inflorescence prior to harvest (Powles 1993). Specialised seed catching systems for headers are now available which consist of an extended sieve to allow seeds to be collected into a separate bin (Jaeschke 1993). The feasibility of using specialised seed catchers to collect wild oat seeds is unlikely because the seed is shed early (Wilson 1970; Matthews *et al.* 1994). Furthermore, seed collection from combine harvesting will remove only 20% of the wild oat seed that has remained attached to the panicle (Cussans 1976).

Medd (1985) commented that abscisic acid is the chemical responsible for wild oat dehiscing but did not suggest how this knowledge might be used to prevent or reduce wild oat seed shedding. Hurtt *et al.* (1977) attempted to halt wild oat seed dehiscence with three compounds applied at various growth stages but failed to improve panicle seed retention. One approach that may remove large quantities of seed is the early harvesting of crops for silage or hay making, but this technique is not commonly used in Australia.

1.4.2. Roguing

The removal of wild oats plants or their reproductive parts is suitable for very low infestations and is recommended by Thurston (1956) and Elliott (1972). The aim of roguing is to either eliminate infestations or reduce them so that herbicide options are delayed. It is important to note that wild oat seeds ripen unevenly because of variations in plant development (Wilson

1970). Furthermore, the seeds in the apex of panicles mature first and are shed before the lower seeds are mature (Thurston 1962). Therefore it is important to remove the entire plant prior to the maturation of the first seeds.

The success of roguing wild oats, from overseas experience, is contradictory. Roebuck and Field (1978) could not reduce wild oat populations by roguing for nine years, even though they kept annual infestations relatively constant in the United Kingdom. Roguing was successful in combination with herbicide in the Netherlands over a period of three years (Naber *et al.* 1992). Failure to contain wild oat populations by intensive hand roguing for four years was reported by Elliott (1972), although some farmers did have success with roguing. Glyphosate can be applied to individual wild oat plants, termed as 'chemical roguing' by May (1972), which is described in Chapter 1.4.3.

1.4.3. Regulating seed production of wild oats

The first attempt to regulate wild oat seed production in crops using chemicals was made by Knowles (1953), using maleic hydrazide. The results from this work were encouraging because the seeds produced were almost entirely non-viable and applications resulted in no phytotoxicity to barley. Although maleic hydrazide showed some potential, Carder (1954) stated it was unlikely to be tested further for toxicological reasons and the narrow 'timing window' required for success. In contrast, Andersen and Helgeson (1954) found that dalapon only reduced wild oat seed production by 30% and whilst germination of seeds was unaffected, seedlings failed to develop further (Andersen and Helgeson 1958). Testing of plant growth regulators 2,4-D, 1-naphthaleneacetic acid and 2,4,5-T applied at various growth stages to wild oats, reduced seed production by up to 46% (Hurtt *et al.* 1977). May (1972) used 5 and 10% v/v solutions of glyphosate applied by hand, using a pad saturated with the solution and applied the solution to emerged panicles of wild oats in barley, a technique termed 'chemical roguing'. Applications were made in the soft and hard dough stage and few of the seeds produced germinated (< 26% of seed produced), with less than 1% developing into healthy plants. This led to the development of the 'roguing glove', a technique which was shown to be three times faster than hand pulling wild oat plants, however a proportion of

non-viable seeds that remained after treatment contaminated harvested grain (Holroyd and Strickland 1978).

Findings following the use of flamprop and its analogues are summarised in Table 1.1. Allen and Butler (1980) found that difenzoquat (0.83 kg a.i./ha) and flamprop-methyl (0.75 kg a.i./ha) when applied to wild oats at the four to five leaf and early jointing stages, respectively, reduced panicle production by 91 to 100% at two sites.

Table 1.1. Summary of research involving the prevention of normal seed production of wild oats.

Reference	Crop(s)	Chemical(s)	Optimum timing (wild oat growth stage)	Efficacy
Warley (1974)	Barley	Flamprop-isopropyl	End of tillering to 1st node	Approx. 85% reduction of panicles averaged over ten countries
Haddow *et al.* (1978)	Wheat & barley	L-flamprop-isopropyl	Late tillering to 2nd node	95% spikelet reduction over five years
Jensen (1990)	Barley	Flamprop-M-isopropyl	Early to late boot	Seed production reduced > 90%
Peters (1990)	No crop	Flamprop-isopropyl, benzoylprop-ethyl and flamprop-methyl	Water ripe stage	42% reduction in dormancy with flamprop-isopropyl
Medd *et al.* (1992)	Wheat	Flamprop-methyl and fenoxaprop-ethyl	Mid jointing to panicle emergence	96% and 92% reduction of seed production for flamprop-methyl and fenoxaprop-ethyl,
Murphy *et al.* (1995)	Wheat & barley	Flamprop-M-isopropyl	Early to mid jointing	Floret number reduced between 91 and 100%

It is evident that flamprop and several of its analogues when applied at the jointing stage of wild oats can bring about substantial reductions in reproductive output, generally without causing unacceptable phytotoxic effects to the crops (Warley 1974; Murphy *et al.* 1995) and may also apply to fenoxaprop-ethyl. However, it is evident that the efficacy of flamprop and its analogues is sensitive to the time of application. Furthermore, after investigating several bioeconomic simulations, it was suggested by Pandey and Medd (1990) and Medd and Pandey (1993) that reductions in seed production must exceed 70% compared with seed production of conventional treatments, to be economically feasible.

1.5. *Conclusions and experimental objectives*

It is evident from the literature reviewed that the persistence of wild oats in Australia results primarily from the continual replenishment of the seed bank from in-crop seed production, not from the build up of seed in the soil due to dormancy. Some factors that affect in-crop seed production cannot be controlled directly by farmers and the remaining factors that might be optimised to reduce seed production are unlikely to result in sufficiently large reductions to bring about the depletion of wild oat populations over time. Therefore, there is scope for developing a more reliable technique that minimises in-crop seed production of wild oats.

Although there is strong evidence supporting the late post-emergence applications of flamprop analogues and fenoxaprop-ethyl for the reduction of wild oat seed production in crops, more research is needed to understand fully the factors involved with selective control of seed production. Consequently, the overall objective of this thesis was to define optimal conditions under which herbicide treatments provide maximal reductions in wild oat seed production in wheat crops using the two most promising herbicides identified.

In order to develop treatments using either fenoxaprop-p-ethyl (a new formulation of fenoxaprop-ethyl) or flamprop (either as flamprop-methyl or flamprop-M-methyl) that minimise in-crop seed production of wild oats, the specific aims were to:

- define the optimum wild oat growth stages at the time of herbicide application under controlled environment and field conditions;
- investigate the benefits of adding adjuvants to herbicide solutions and consequently define the optimum herbicide rate;
- define the wild oat growth parameters that contribute to the reductions in wild oat seed production after late post-emergence applications of these selective herbicides;
- measure several aspects of wheat phytotoxicity to test if these late post-emergence applied treatments have any adverse effects; and
- test the hypothesis that population control can be achieved by reducing seed production using late post-emergence applications of flamprop.

Chapter 2. General methodology

This chapter describes the materials and methods common to the majority of the field experiments reported in this thesis. Methodology specific to individual experiments is outlined in the relevant chapters.

Fenoxaprop-p-ethyl 69 g a.i./L (Puma®S) and flamprop-M-methyl 75 g a.i./L (Mataven®L) were the herbicides used in most of the experiments. During the experiments undertaken in 1992, flamprop-methyl 100 g a.i./L (Mataven®100) was used as the 'Mataven' treatment. The standard recommended dose rate (RDR) for early post-emergence applications of fenoxaprop-p-ethyl is 34.5 g a.i./ha (Puma®S at 500 mL/ha), and that for flamprop-M-methyl is 225 g a.i./ha (Mataven®L at 3 L/ha) and flamprop-methyl is 450 g a.i./ha (Mataven®100 at 4.5 L/ha). Flamprop-methyl contains equal quantities of an active ('L') and an inactive ('D') isomer. In contrast, flamprop-M-methyl consists only of the 'L' isomer. Collective references to both flamprop-methyl and flamprop-M-methyl will be referred to as flamprop throughout the thesis.

2.1. *Field experiments*

All field experiments, except for the long term validation experiment at Tamworth (Lat. 31°9'S, Long. 150°59'E) (Chapter Seven), were conducted within three successive seasons from 1992, in commercial wheat crops infested naturally with wild oats. These experiments were located in the northern NSW grain belt, four at Crooble (Lat. 29°15'S, Long. 150°11'E), three at Inverell (Lat. 29°45'S, Long. 151°12'E), two at Somerton (Lat. 30°59'S, Long. 150°40'E) and one at Tulloona (Lat. 28°57'S, Long. 150°2'E) (Table 2.1). Black self mulching clay soils were common to all sites.

2.1.1. Site selection, data collection at spraying and herbicide application

A prerequisite for site selection was an experimental area with uniformly distributed light to moderate wild oat densities, approximately 10 to 40 plants per m^2. Sites with the healthiest crop and weed growth were selected and potential sites were rejected if the wheat cultivar was known to be sensitive to flamprop. For example, the wheat cultivars Sunelg, Kite; Eagle, and Meteor

are recognised as susceptible cultivars, particularly if treated after full tillering (growth stage Zadoks decimal code (DC) = 29 as outlined by Zadoks *et al.* (1974)).

Table 2.1. Coding and a description for field experiments used to evaluate the potential of late post-emergence applications of selective herbicides.

Experiment Code	Location	Year	Brief description of the experiment
IN92RXT	Inverell	1992	Effects of herbicide rate and application time.
CR92RXT	Crooble	1992	Effects of herbicide rate and application time.
IN93RXT	Inverell	1993	Effects of herbicide rate and application time.
IN93MVM	Inverell	1993	Evaluation of two formulations of flamprop.
CR93MVM	Crooble	1993	Evaluation of two formulations of flamprop.
CR93ADJ	Crooble	1993	Using adjuvants to improve herbicide efficacy.
T93WVT	Tulloona	1993	Wheat cultivar herbicide tolerance experiment.
CR94ADJ	Crooble	1994	Using adjuvants to improve herbicide efficacy.
SM94ADJ	Somerton	1994	Using adjuvants to improve herbicide efficacy.
SM94RXT	Somerton	1994	Effects of herbicide rate and application time.

General environmental conditions including wet and dry bulb temperature (°C), relative humidity (%), boom nozzle size and herbicide spray volume (L/ha), wind direction, cloud cover (%) and wind speed (m/s), along with a subjective assessment of plant / weed vigour were recorded immediately after herbicide application. Relative humidity was derived from meteorological charts using the wet and dry bulb temperatures obtained from a whirling psychrometer. Wind speed was measured using a hand held battery powered anemometer, or was subjectively estimated if no anemometer was accessible. The anemometer was held into the direction of wind for 60 seconds and maximum, minimum and average wind speeds, were recorded, or else were categorised according to wind strength whenever assessed subjectively. Other details including paddock history, wheat cultivar, fertiliser applications (kg/ha), sowing rate (kg/ha) and sowing date and were also obtained from the farmer, and recorded at the date of spraying.

Wild oat and wheat densities (plants/m^2) were assessed immediately prior to spraying in four 0.25 m^2 quadrats placed in a stratified pattern along the plots (pre-counts). Growth stages were assessed from 20 randomly collected wild oat and 20 wheat plants removed from each replicate block. For each plant the standard assessment of the main shoot (Zadoks *et al.* 1974), together with the growth stage of tillers was assessed and classified into either vegetative, elongating, booting or inflorescence categories. For the purpose of this thesis, all tillers and the main shoot are termed collectively as tillers. The vegetative category consisted of tillers ≤ 20 Zadoks DC; elongating tillers were ≥ 30 to ≤ 39 Zadoks DC; tillers in boot were ≥ 40 to ≤ 49 Zadoks DC and tillers in inflorescence had a Zadoks DC ≥ 50. Plant growth stages were then presented as the percent of tillers designated within one of the four growth categories.

Treatments were applied with a hand held boom spray (Figure 2.1) covering an area of 3 m by 10 m within 4 m by 10 m designated plots, thus leaving 0.5 m buffers on the longitudinal edges of each plot. A pressure regulator maintained a constant spraying pressure of 240 kPa through Teejet® flat fan nozzles, positioned 50 cm apart and 45 to 50 cm above the crop / weed canopy. Pressurised CO_2 was used as the propellant. Herbicide spray volumes ranged between 133 and 189 L/ha. The speed of the boom was limited to the walking speed of the operator. To ensure no contamination of spray solutions, the boom was flushed with water between each treatment application.

Figure 2.1. Application of herbicides using a 3 m wide hand held boom, pressurised with CO_2.

Wild oat and wheat densities (plants/m^2) were assessed immediately prior to spraying in four 0.25 m^2 quadrats placed in a stratified pattern along the plots (pre-counts). Growth stages were assessed from 20 randomly collected wild oat and 20 wheat plants removed from each replicate block. For each plant the standard assessment of the main shoot (Zadoks *et al.* 1974), together with the growth stage of tillers was assessed and classified into either vegetative, elongating, booting or inflorescence categories. For the purpose of this thesis, all tillers and the main shoot are termed collectively as tillers. The vegetative category consisted of tillers ≤ 20 Zadoks DC; elongating tillers were ≥ 30 to ≤ 39 Zadoks DC; tillers in boot were ≥ 40 to ≤ 49 Zadoks DC and tillers in inflorescence had a Zadoks DC ≥ 50. Plant growth stages were then presented as the percent of tillers designated within one of the four growth categories.

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Figure 2.1. Application of herbicides using a 3 m wide hand held boom, pressurised with CO_2.

2.1.2. Post-spraying assessments (wild oats)

The number of wild oat seeds set per spikelet (spikelet seed set) was assessed by harvesting at least 200 spikelets (10 to 50 panicles, depending on treatment effects) from each plot, prior to the start of seed shedding (seed rain). These data provided an index to spikelet seed set, and this is termed 'seed indexing'. Wild oats were hand harvested, as entire plants in 1993 and 1994, prior to mechanical harvesting of wheat. In 1992, only wild oat panicles were harvested. Panicles and plants were harvested from four 0.25 m^2 quadrats placed evenly in a stratified pattern along the middle longitudinal section of each plot. Within these, plant (other than the 1992 experiments), panicle (panicles/m^2) and spikelet densities (spikelets/m^2) were assessed. Wild oat seed production (seeds/m^2) was assessed by counting glumes or pedicels on the panicles harvested after maturity and multiplying by two, or by the estimate of spikelet seed set (seed index) when this was assessed (Wilson 1981c). Wild oat seed production (seeds/m^2) was therefore derived from measured parameters (refer to Table 2.2 and Figure 2.2).

Mechanical harvested samples from each plot were graded to separate wild oat seeds from wheat (1993 and 1994 experiments). A measure of wild oat seed contamination in wheat was obtained from this process to assess wild oat seeds removal per m^2.

2.1.3. Post-spraying assessments (wheat)

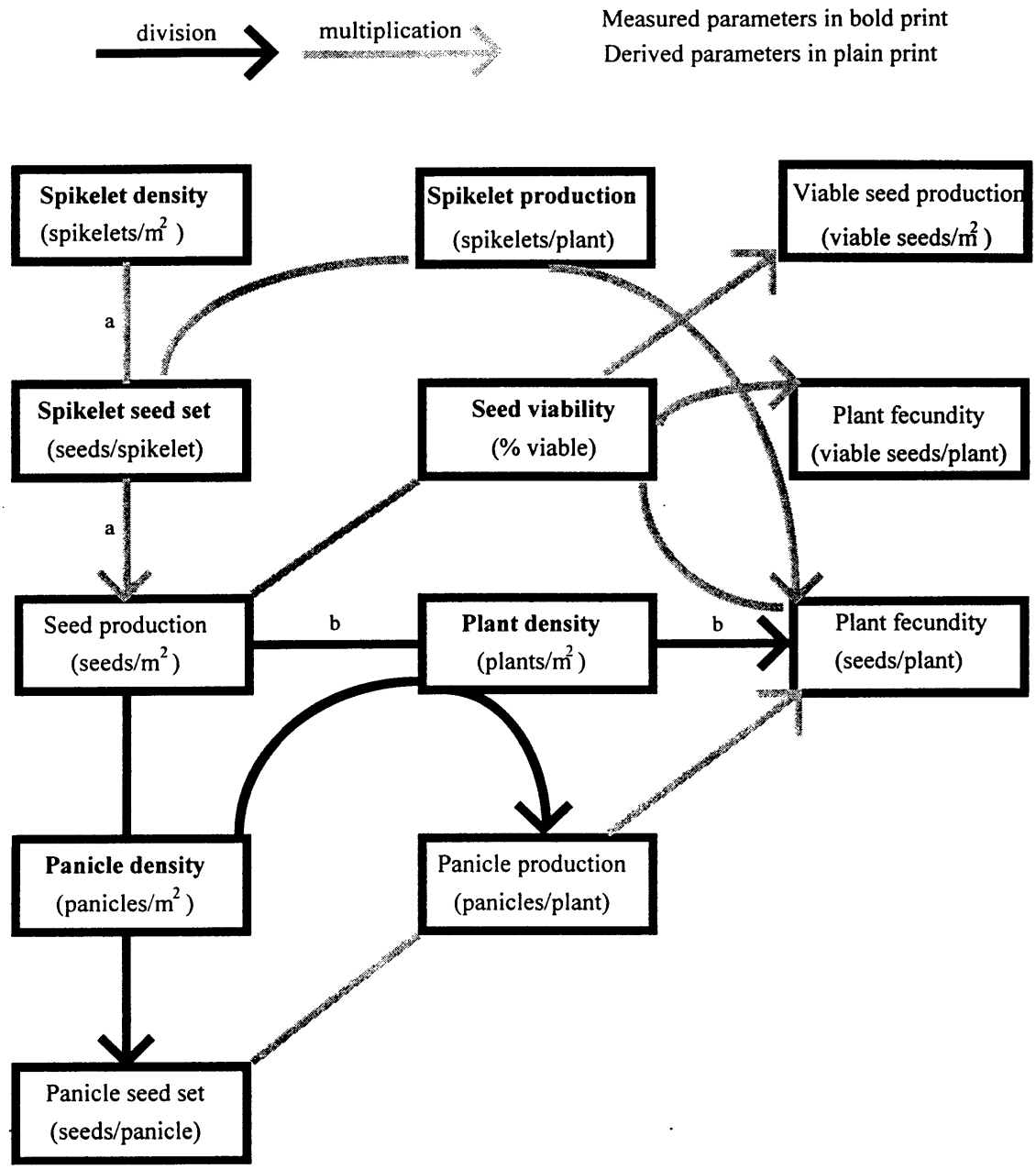
Wheat height, an indicator of phytotoxic damage, was also measured around physiological maturity, prior to harvest. Twenty tillers chosen at random along the length of each plot were assessed to obtain a reliable estimate of wheat height. The definition used to measure wheat height was the distance (cm) from the crown (ground level) to the top of the last spikelet. A measure of grain size, i.e. 1,000 seed (kernel) weight (g) was assessed from hand or mechanically harvested samples using an electronic seed counter (Numegral® seed counter).

Yield (t/ha) was calculated from either hand or mechanically harvested samples. Mechanically harvested samples were obtained using a small plot header (Kingaroy engineering works Pty. Ltd.) and hand harvesting of wheat heads was undertaken by removing whole plants from within the same quadrats used to assess wild oat parameters at harvest (Chapter 2.1.2).

Table 2.2. A summary of the measured or derived parameters, their respective units, use within experiments or seasons and associated terminologies (also applies to pot experiments).

Variable	Units	Experiment(s) or season(s) in which the variable was measured
Measured parameters		
Wheat:		
Density (pre-count)	plants/m^2	1993 and 1994
Height[a]	cm	T93WVT and 1994
1,000 seed weight[b]	g	1992, 1994, CR93ADJ and T93WVT
Yield[b]	t/ha	1992, 1994, all 'CR93' experiments, T93WVT
Plant density[b]	plants/m^2	T93WVT
Wild oats[c]*:*		
Density - (pre-count)	plants/m^2	1992 to 1994
Seed contamination in wheat grain[b]	seeds/m^2	1994
Plant density[b]	plants/m^2	1993 and 1994
Panicle density[b]	panicles/m^2	1992 to 1994
Spikelet density[b]	spikelets/m^2	1992 to 1994
Spikelet seed set[a] (seed indexing)	seeds/spikelet	1993 and 1994
Derived parameters		
Wild oats:		
Seed production[b]	seeds/m^2	1992 to 1994
Panicle production[b]	panicles/plant	1993 and 1994
Panicle seed set[b]	seeds/panicle	1992 to 1994
Fecundity[b]	seeds/plant[d]	1993 and 1994

[a] An intermediate (in-crop) assessment.
[b] Assessment made at crop / wild oat maturity.
[c] Wild oats were not assessed in experiment T93WVT.
[d] Also applies to viable seeds/plant for pot experiments only.



Examples: [a] Spikelet density x Spikelet seed set = Seed production (derived variable)

[b] Seed production ÷ Plant density = Plant fecundity (derived variable)

Figure 2.2. The relationship between measured and derived wild oat reproductive parameters (includes some production parameters relevant to the pot experiments).

2.1.4. Statistical analyses

Data from individual experiments were analysed statistically using Genstat 5 (Payne *et al.* 1987). Experimental designs were either randomised complete block or split-plot designs. An untreated control treatment was analysed as a separate factor and the remaining treatments were analysed as factorial effects. Pre-spraying wild oat densities (pre-counts) were tested and used as covariates where appropriate. A generic program was constructed to test for the effects of covariates and to determine if transformation of data was necessary to normalise variance. The appropriate transformation, generally either square root or logarithmic (natural), was accepted if the plotted residuals showed that variance was homogeneous. Once the optimal adjustments were determined, data were analysed using ANOVA (analysis of variance). Standard error of difference (s.e.d.) values were used to determine differences between treatments or treatment effects.