
Chapter 9

WEED MANAGEMENT ON ARABLE LANDS

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Throughout agricultural history, tillage has been inextricably linked with weed control. In all its forms, tillage has had three possible functions regarding weeds:

- * to animate propagules;
- * to kill emerged plants prior to growing the crop; or
- * to kill plants within a crop.

The first major use of organic herbicides since their discovery has been their substitution for cultivation within the crop. Over time, a broader range of more specific herbicides has become available, allowing the further substitution of chemicals for tillage in pre-planting weed control. These developments have not only been economically fortuitous but highly desirable in conserving soil resources. However, chemicals that can be economically applied to substitute for the role of tillage in animating propagules have yet to be discovered.

The control of weeds in farming systems is not achieved simply by cultivating or applying chemicals. Weeds are biologically devious and can only be eliminated with highly intensive treatment that is generally far beyond that affordable in broadacre agriculture.

In today's farming systems some form of weed suppression is involved in almost every operation of crop production. Many operations, such as cultivation and the application of herbicides, are specific and directly attack weeds. Other means of control are less obvious, like the choice of crop species and cultivar, fertiliser inputs, crop density and time of sowing. Weed management involves the enmeshing of all of these methods in a planned way to form control strategies.

Consequently, weed management is about efficiency - obtaining the best economic result from the most feasible combination of inputs. It is concerned with minimising losses due to the presence of weeds, maximising weed mortality and limiting the amount of weed seed produced. Weed management involves both tactical short-term, and strategic long-term, objectives aimed at preventing an unacceptable population increase (Cussans and Moss, 1982). Commonly, control practices aim to restrict weed populations to some arbitrary level and, in general, greater emphasis is placed on controlling the active (growing) component of weed populations. This is based on the supposition that it is only relevant to control the active component during the life of a crop because it reduces yield or causes damage. Less emphasis has been placed on controlling the passive components (inactive seeds or other propagules in the soil), because of a poor understanding of how they may be regulated and the lack of commercially feasible methods for treating them. Preoccupation with control of the active population is not necessarily efficient in the long term, as is evident from the persistence of populations of weed species as a whole, since passive reserves provide a source of propagules for reinfestation.

The need for more **systematic** approaches to weed control is perhaps greater now than in the past due to the rapid changes taking place in farming systems and the adoption of conservation

farming practices. Any judgement of the effects these changes are having on weeds must inevitably be based on the behaviour of weed populations and so requires a thorough understanding of both plant and propagule biology.

THE WEED FLORA

Over 430 species (70% of which are dicotyledons) in 59 families have been nominated as arable weeds in Australia (P.W. Michael, unpublished working checklist). Only a few of these species are of major importance. However, the weed flora differs between fields, farms, regions, climatic zones and cropping systems. Furthermore, the spectrum of species within a field is influenced by farming practices such as tillage and the application of herbicides and fertilisers.

Two aspects - the correct identification of weeds, and an examination of how and why particular practices affect changes in the weed flora - are considered in this section.

IDENTIFICATION AND TAXONOMY

Taxonomy is an important foundation to weed management. Correct identification of weeds ensures the application of appropriate knowledge and control measures. This is especially necessary when dealing with mixed species and species complexes that react differently to particular control measures. Errors in identification abound and inevitably result in confusion and expensive mistakes by failing to control the target.

As McNeill (1982) emphasised, many important cropping weeds are the subject of some taxonomic difficulty. In diverse species complexes like the *Xanthium strumarium sens. lat.* group (McMillan, 1975), or genera such as *Echinochloa* (Michael, 1983), *Amaranthus* (Michael, 1978) and *Lolium* (Kloot, 1983), the species are clearly defined but variation within the species clouds any determination. Confusion among closely related species of similar phenotype, for example annual *Phalaris* species, can likewise lead to error.

Other difficulties in identifying weeds arise from inadequate taxonomic study, the need to identify weeds in vegetative stages (for control purposes) or to identify propagules (as contaminants of produce). In the case of inadequate taxonomy, species new to an area or previously regarded as being of minor importance may not be included in identification manuals. In addition, weed manuals often distinguish between only the more common species and inadequately treat less conspicuous non-weedy taxa or newly formed hybrids (McNeill, 1976). With Brassicaceae and Solanaceae, for example, in which many non-weedy members exist, it is necessary to refer to floras that treat entire families. *The Flora of Australia* (Bureau of Flora and Fauna, 1981-) has enormous value in this regard but as few families have been completed in this ongoing work it will remain necessary to use identification services at recognised herbaria. Manuals describing vegetative and propagule forms are almost non-existent for Australia and again professional help from herbaria and seed laboratories should be sought to ensure correct determination. In every context, it is imperative that samples be collected and preserved appropriately as vouchers (Auld, 1984a). This applies equally to all facets of weed research, extension and practice.

A well documented case involving taxonomic complexities occurred in the control of *Chondrilla*

juncea (skeleton weed) in Australia using biological agents. Three biotypes or races of *C. juncea* differing in leaf shape, inflorescence morphology and fruit characters were recognised and the geographic distribution of each recorded (Hull and Groves, 1973). In 1971, organisms, including a rust fungus *Puccinia chondrillina*, were released for biocontrol of the weed. The strain of the fungus released was specific to the most widespread biotype of the weed and has been responsible for a significant reduction in density (Cullen and Groves, 1977; Cullen, 1978). The niche previously occupied by that biotype is now being filled by the other two biotypes (Burdon *et al.*, 1981). Strains of the fungus specific to one of these biotypes have now been released, while a strain specific to the third biotype has yet to be discovered (Davidson, 1983). This example emphasises how specific taxonomic detail can affect weed management; as discussed below, some herbicides likewise selectively affect biotypes within specific populations.

Global taxonomic agreement is equally necessary for meaningful communication. An example of international confusion involved the mis-identification in reporting atrazine resistance in *Amaranthus* spp. (Warwick and Weaver, 1980). Although the error was discovered quickly the lack of voucher specimens meant that the original occurrence of resistance cannot be precisely retraced.

SHIFTS IN WEED FLORA

The floras of arable land are not stable. Each field has its own flora, which in part reflects its history. Such communities may consist of one or more dominant species and subordinate species as active components. Control practices are commonly directed towards dominants and may opportunistically affect subordinates, or, if unaffected, these may rise to dominant status. Subordinate species having large passive reserves in the soil can also rise to dominant status with changes in cultural practices, such as an alteration in tillage methods. Concurrently there is always the possibility for new species to invade or be introduced, thus providing a basis for change in the flora. The appearance of herbicide-resistant biotypes within species is another expression of floristic dynamism. All such shifts in flora are important reasons for devising integrated weed management programmes to achieve optimal efficiency in weed control.

European experience

Froud-Williams *et al.* (1983a), in a study of four fields in England, showed that while up to 30 species occurred as passive components of the seed bank, only three or four of these were dominant in the active flora. The dominants were mostly annuals and all had considerable seed reserves in the soil. By contrast, *Polygonum aviculare* (wireweed) a major constituent of the passive flora, was poorly represented (subordinate) in the active flora, as was *Juncus bufonius* (toadrush). Both species characteristically have high fecundity and prolonged seed longevity. (Such reserves may be relics of plant associations developed under previous and not necessarily arable uses of land (Numata, 1982).) Although different tillage treatments and crop rotations were tested, there was no evidence of change in the dominant species of the active flora during this study. However, subdominant species even with small passive reserves can become dominant in response to changed management. For instance, annual grass weeds have become more prevalent with the adoption of reduced tillage in Europe (Froud-Williams *et al.*, 1981). Other studies suggest that tillage redistributes seed within profiles (Pareja *et al.*, 1985) and influences the active flora that generally arises from seed in the surface stratum (Roberts, 1981); but this depends on seed size, age of seeds, frequency and type of tillage and the proportion of seeds giving

rise to seedlings. Consequently, species respond differently to varying types of tillage as shown by Pollard and Cussans (1981), Pollard *et al.* (1982) and Froud-Williams *et al.* (1983b).

One of the best documented examples of changes in the weed flora of arable fields compares sprayed and unsprayed fields in Denmark using ordination techniques (Haas and Streibig, 1982). As in many countries, the tendency in Denmark since the early 1950s has been to grow monocultures of winter cereals continuously, with increasing inputs of fertiliser and herbicide. Before then, cultural practices changed little from those used for centuries except for more frequent and possibly more vigorous tillage with the coming of mechanisation during the first part of this century.

While changes in the composition of weed species have continually occurred, there was only minor change in the overall number of species infesting arable fields. The analyses indicated that these changes were evident before the organic herbicides came into use. Such changes were influenced more by the species of crop in which the weeds were growing than by tillage practices. Also, the distribution of annual weed species and their frequency correlated closely with the growth period of crops, suggesting that some crops were more competitive towards weeds than others.

Haas and Streibig (1982) found that particular species showed adaptations to habitats and cultural operations. For example *Poa annua* (winter grass) dominated in grass leys; *Stellaria media* (chickweed) occurred at high frequency in both winter and summer annual crops; and the perennial, *Elymus* (syn. *Agropyron*) *repens* (English couch) was largely unaffected by the growth period of the crop (Figure 9.1). Liming of soil reduced the occurrence of calcifuge species, whereas the increased use of nitrogen fertilisers (three-fold in Denmark since 1950) especially encouraged grasses. Still other species were favoured by phosphorus and potassium usage. In addition, the use of herbicides has escalated: in Denmark more than 4000 t are used annually, 64% of which is applied to cereals. The phenoxy acids account for 80% of this usage. Consequently, fields are being exposed to the same herbicides more frequently. Thirty years of continual use of MCPA on spring cereals had little effect on the relative biomass of weed produced, whereas in areas not sprayed in the experimental year the relative weed biomass decreased (Figure 9.2). This decrease in relative weed biomass is probably largely due to increased crop biomass (assuming constant harvest index), hence absolute weed biomass may not have changed. This could explain why the difference in crop grain yield between unsprayed and MCPA-treated areas remained constant, even though grain yield continued to increase over the period (Figure 9.2). Irrespective of the biomass differences, the composition of the flora changed, with a tendency for species highly susceptible to MCPA to retreat, and more tolerant species to increase.

Changes in the flora of arable fields in England reinforce the generalisation that cropping sequences, tillage regimes, the use of chemicals and other cultural operations selectively produce short-term responses (Froud-Williams *et al.*, 1981). Species suppressed under one regime, re-emerge given favourable circumstances. Rarely are species eliminated and, for the few species that have been, their disappearance is attributed to specific techniques such as improved seed cleaning (Godwin, 1956), changes in soil pH (Fryer and Chancellor, 1970), or improved land drainage (Salisbury, 1961).

Australian experience

There are few documented studies of changes in the flora of arable weeds in Australia. One example (Amor and de Jong, 1983) chronicled changes in problem weeds in winter cereal cropping in Victoria since 1920. Prior to 1940 the dominant weeds were *Avena* spp. (wild oats), *Sisymbrium*

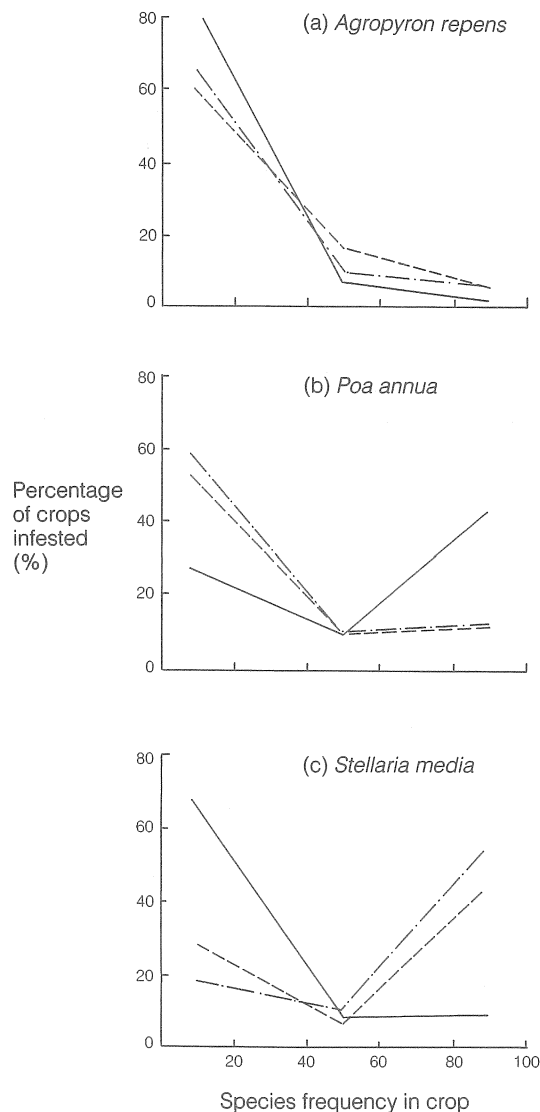


Figure 9.1 Frequency of occurrence of (a) *Agropyron repens*, (b) *Poa annua*, and (c) *Stellaria media* in three cropping systems (adapted from Haas and Streiberg, 1982): (—) grass ley, (----) winter annual crop, (— · —) summer annual crop

spp. (wild mustard), *Cardaria draba* (hoary cress), and *Carthamus lanatus* (saffron thistle). Two other grasses and nine broadleaf species sporadically dominated in certain seasons. During this period weed control relied mostly on timely and repeated tillage.

Over the next two decades all the above species remained as problems. Additional species, which had not previously been common, became dominant. These included *Brassica tournefortii* (wild turnip), and *Raphanus raphanistrum* (wild radish), and two perennial Asteraceae, *C. juncea* and *Acroptilon repens* (creeping knapweed). Two other grasses and seven new broadleaf weeds also became prevalent during this period. In common with the events described for Europe, herbicide usage (especially phenoxy acids) increased markedly between 1950 and 1960 (see also Chapter 1). Yet many more weed species appeared without any existing dominants being replaced (Amor and de Jong, 1983).

The trends in Victoria during the 1960s typified those experienced throughout the winter-rainfall areas of southern Australia. Brassicaceae species susceptible to the phenoxy

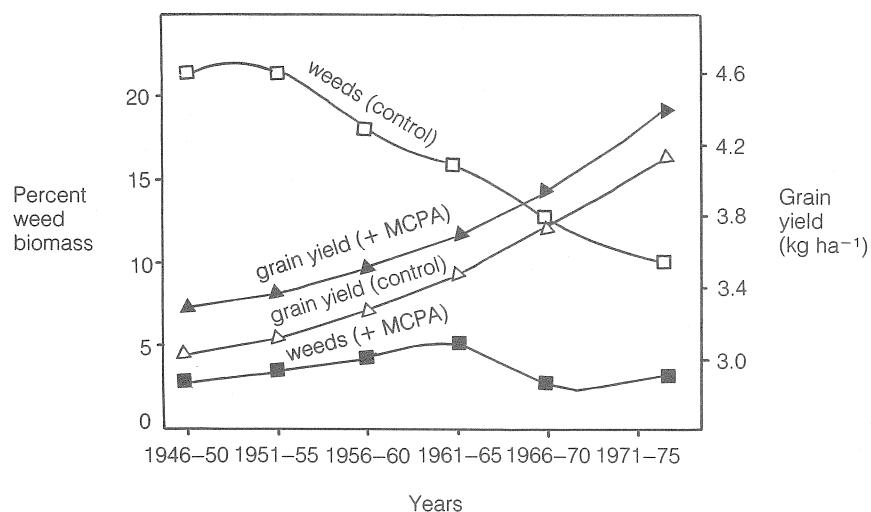


Figure 9.2 Effect of MCPA herbicide on grain yield of spring cereals and relative weed biomass (percentage of total biomass). Closed symbols indicate MCPA treated and open symbols, untreated in the experimental year. Data from > 4000 field experiments in Denmark (Haas and Streiberg, 1982)

acid herbicides declined, while tolerant species like *Fumaria* spp. (fumitory), *Lithospermum arvense* (corn gromwell), *Lamium amplexicaule* (deadnettle), *Emex* spp. (spiny emex) and *Amsinckia* spp. (yellow burr weeds) all increased in occurrence. When the use of phenoxy acids was relaxed, some of the suppressed species re-emerged, indicative of a requirement for current farming systems to maintain broad-spectrum control. For the first time in 50 years some weeds were displaced. But new species continued to emerge; only one of these, *Lolium rigidum* (annual ryegrass) had previously been prevalent. Another grass, *Bromus* sp. (brome grass), two more perennials *Oxalis pes-caprae* (soursob), and *Allium vineale* (wild garlic), and one broadleaf, *Polygonum aviculare* became prevalent.

A recent survey of Victorian fields confirms there has been an overall increase in the number of common weeds (at least 87 species, 71% of which are annuals and 27% perennials (Amor, 1984)) while very few species have been suppressed. There is likewise a broad range of weeds in winter cereals in northern New South Wales (Martin and McMillan, 1984) and in Tasmania, where in recent years three species of *Polygonum* have increased due to spread by machinery (Hyde-Wyatt, 1982).

Based on the trend experienced in North America (Wicks, 1985) and Europe it was to be expected that annual grass weeds would be favoured by the adoption of reduced cultivation systems in Australia. Observations have borne this out. For example, *Hordeum leporinum* ssp. *glaucum* (barley grass) (A.D. Rovira and R.L. Correll, personal communication, 1985) and *Vulpia* spp. (silver grass) (F. Forcella, personal communication, 1983) have become more prevalent in the absence of full seedbed disturbance in south-eastern Australia. Changes in annual broadleaf weeds have also been observed in reduced tillage systems. Some have become less common, others such as *Capsella bursa-pastoris* (shepherd's purse) and *Lactuca serriola* (prickly lettuce) may increase (R.L. Amor, personal communication, 1983).

Amor has also predicted that many perennial broadleaf weeds will proliferate in the absence of soil disturbance. One study involving *Rumex acetosella* (sorrel) in north eastern Victoria (G.R. Code and T.G. Reeves, personal communication, 1983) has signalled that this weed is also adapted to reduced tillage systems.

Predicting changes in weed flora

Clearly, agricultural practices bring about changes in weed floras but throughout the world only a few species have been eliminated. These changes occur gradually and are mostly the result of interacting elements such as herbicides, fertilisers, tillage and cropping sequences and crop types. It is also evident that a weed species may behave differently in different regions due to variation in climate. Methods that can predict species changes are needed so that control strategies can be modified to prevent such changes (especially the invasion of species known to be difficult to control) or made suitable for treating the new problem. This is particularly important in Australia where, unlike in Europe, the trend has been for the total number of weed species to increase on arable land.

Surveys are valuable for monitoring weed infestations but few large scale surveys undertaken to date have been successfully designed to enable time trends to be studied. For instance, the lack of standardisation (in region surveyed, sampling technique, time of surveying, and species recorded) makes it difficult to interpret time changes in infestations of annual grass weeds in crops in the United Kingdom. This applies in particular to the surveys reported by Thurston (1954), Elliot and Attwood (1970), Phillipson (1974), Chancellor (1977), Froud-Williams and Chancellor (1982) and Chancellor and Froud-Williams (1984). By contrast, the system developed in Canada (Thomas, 1979; 1985) has been designed to provide information about current and long-term trends in weed distribution, abundance, associations and the competitive impact of weeds. Such surveys are labour intensive and costly to undertake but if carefully designed can provide data appropriate to the needs of weed management (Auld, 1984b).

While surveys of particular weed species or floras within regions (e.g. *Avena* spp. Paterson, 1976; c.f. Velthuis and Amor, 1983; Martin and McMillan, 1984) have been done, there is no national system of monitoring weed floras in Australia. Consequently there will be limited opportunity to predict changes and develop anticipatory control methods unless resources are allocated to recording the composition and changes in weed floras.

HERBICIDE RESISTANCE

Shifts in species composition in monocultures, where repeated doses of the same herbicide are applied, is an expression of variable tolerance or susceptibility. By contrast, resistance involves a changed response such that a previously susceptible species shows immunity to a herbicide.

Unlike the widespread occurrence of resistance of other agricultural pests to pesticides, there has been, to date, limited expression of this phenomenon among weeds. Most field cases have occurred after a decade or more of applying s-triazine herbicides (notably atrazine and simazine) in Europe and North America (Bandein *et al.*, 1982). Two cases of restricted extent have been reported in Australia. A population of *Lolium rigidum* in South Australia is resistant to Hoegrass (Heap and Knight, 1982). Resistance in *Hordeum leporinum* ssp. *glaucum* (barley grass) to paraquat has also occurred in western Victoria (Powles, 1986). Both incidents have involved a regimen of high doses of the respective herbicide applied repeatedly over several years.

A combination of factors has restricted the expression of herbicide resistance. Compared with other pesticides, herbicides have less specific modes of action and many are less persistent. Also, most weeds have large reserves of propagules of the susceptible biotype, have non-synchronised germination behaviour, comparatively long generation times and resistant biotypes have reduced 'fitness'. These features combine to dilute the selection pressure of

herbicides (see Gressel and Segel, 1982 for detail). The net effects of the interplay of these factors has been twofold: incidence of resistance is low, and expansion or spread of resistant biotypes is slow due to their weaker competitiveness compared with susceptible biotypes (Conard and Radosevich, 1979; Holt and Radosevich, 1983).

Nevertheless these experiences signal that resistance can be expected from abuse or heavy reliance on particular herbicides. Resistance in laboratory cultures to numerous other herbicides, including 2,4-D, diuron, bentazon and picloram has been demonstrated (Meredith and Carlson, 1982; Truelove and Hensley, 1982), and this is indicative of the potential for resistance to increase.

Paraochetti *et al.* (1982) discussed the options for controlling herbicide-resistant weeds and concluded that these would result in greater costs. Since the possibility for resistance increases at a logarithmic rate when herbicides are repeatedly used (Gressel and Segel, 1982), the adoption of agronomic measures to delay the onset of resistance is desirable. Worthwhile measures include minimising the use of persistent herbicides, rotation of herbicides and crops, the use of herbicide mixtures, and a greater reliance on other cultural methods such as those discussed later in this chapter.

WEED POPULATION BIOLOGY

Weed management is in part ultimately concerned with containing or reducing population growth rates. Practices that concentrate on killing plants may succeed in containing populations but there is little likelihood of them eliminating weed problems since invariably many more propagules (buds or seeds) lie uncontrolled in the soil. Arable soils generally contain thousands of seeds per square metre of ground area. Only a portion of these seeds germinate when conditions become favourable; the remainder provide reserves (or banks) from which seedlings continue to emerge sporadically over succeeding years. The magnitude and persistence of seed banks are thus key factors among those responsible for the perpetuation of weeds and, as a consequence, for the continuing need for weed control.

Annual plants begin and end life as a seed. The seed bank is thus a convenient locus for assessing rates of change in populations. The interplay of inputs and losses within a seed bank is vital to understanding the dynamics of populations, so aspects of the biology of these processes are considered in this section. Ways of applying this knowledge to the management of weed populations are discussed in later sections.

SEED BANK ECOLOGY

Function and composition of seed banks

Seeds play a major role in ensuring the survival of species. Tactics used by seeds in pursuit of survival range from having overwhelming numbers, which affords enormous foetal wastage, to complex biochemical and physiological contrivances that confer protection against degeneration, perturbation or inadvertent germination.

Seed banks are composed of propagules from past and present components of a resident vegetation as well as immigrants from other areas (see Figure 9.7). Surveys of arable fields in Europe show that mostly less than 50 000 seeds per square metre exist in the tilled profile but this can range to as high as 500 000 m⁻² (Kropáč, 1966; Roberts and Stokes, 1966; Jensen, 1969; Paatela and Ervio, 1971; Froud-Williams *et al.*, 1983a; Warwick, 1984). As previously discussed, environmental and management factors largely determine the species composition of a seed bank in arable soils. Within species, seed 'quality' varies widely due to genotype, ecotype and the environmental conditions under which seeds mature on the parent plant. This was illustrated by Cheam (1984) for populations of *Raphanus raphanistrum* and *Rumex pulcher* (fiddle dock).

Seeds are distributed both vertically and horizontally in the soil. Seed longevity is particularly influenced by depth of burial and is considered in detail later in this section. In addition, seed banks are made up of seeds of different ages, which imparts distribution in time. Consequently seed banks consist of a mixture of many species, each of which is composed of a pool of seeds of mixed ages and quality. It is this seed-to-seed variation that influences patterns of emergence and the persistence of seeds in the soil.

Seed dormancy

Dormancy is defined as an inability of living embryos to grow given favourable conditions. This form of suspended animation enables seeds to persist in the soil. Dormancy could be due to the absence or blocking of some essential metabolic step within the embryo, or to physical or chemical constraints in membranes external to the embryo (e.g. seed coat). In the former, breaking of dormancy requires the reinstatement of complete metabolic function, whereas the latter requires removal or circumvention of the inhibition.

The complexity of dormancy is well illustrated by research of a multidisciplinary Canadian team working on *A. fatua*. Dormancy in the embryo of this species has been attributed to a multiplicity of reactions (Simpson, 1983). A number of points in the respiratory system can be blocked since various exogenously applied agents (e.g. gibberellin, ethylene, azide and nitrate) have been shown to break dormancy by acting on different pathways. Furthermore, the state or form of dormancy can be affected during genesis as well as after seeds leave the mother plant. As shown by Peters (1982a), seeds of *A. fatua* produced in hot dry conditions were less dormant than seeds formed in cool moist ones. Once dispersed and incorporated into the soil, the state of dormancy and the physical integrity of seed structures may undergo further change, e.g. as reported for *Bromus diandrus* (great brome) (Anderson, 1984) and *C. juncea* (Panetta, 1984). From the outset, therefore, it is possible to visualise that seeds of different species may exist in the seed bank with varying types and degrees of dormancy, and that these undergo continual change.

The dynamic nature of dormancy is illustrated by a number of summer and winter annual species that show consistent and repeated cyclical changes in dormancy of buried seeds. Three phases of the annual cycle can be distinguished: alleviation of dormancy, a period of minimal dormancy, and the reintroduction of dormancy (secondary dormancy) (Figure 9.3). Seeds are generally released from dormancy in the months preceding the season most favourable for germination. Conversely, dormancy is reinstated in the season preceding periods that are unfavourable for plant survival (Karssen, 1982).

Environmental factors have pronounced effects on the maintenance and alleviation of dormancy. Each different expression of dormancy appears to require different environmental cues to bring about its demise. For example, in some summer annuals, cold temperatures are strongly

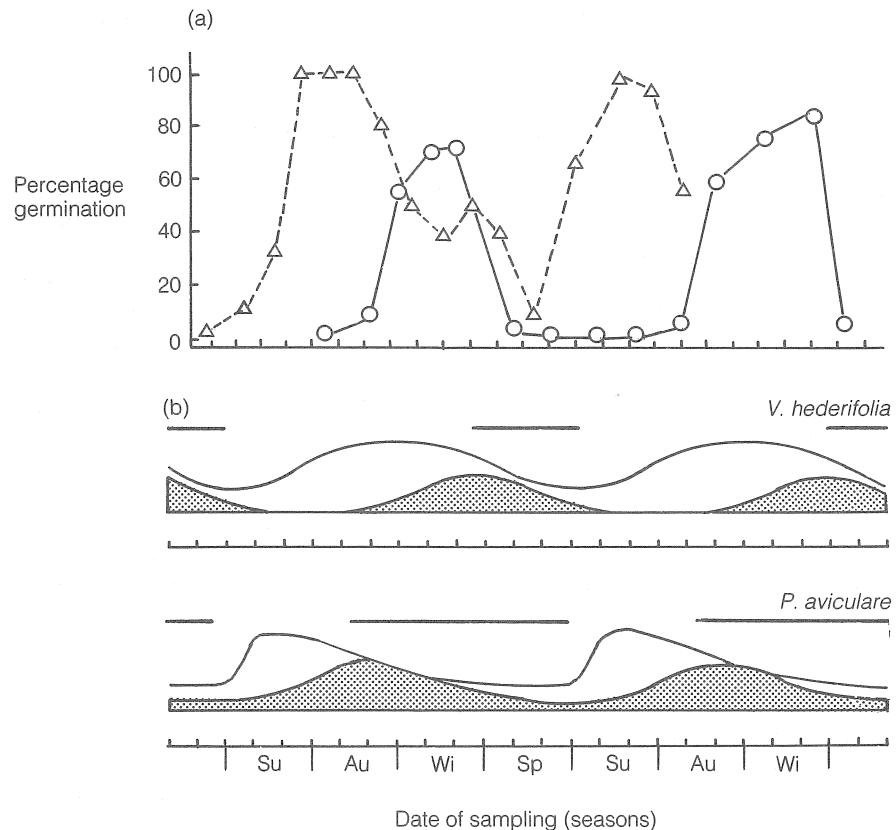


Figure 9.3 Changes in the state of dormancy of buried seeds of *Veronica hederifolia* (Δ) showing that dormancy is overcome during summer and autumn and reintroduced during winter and spring (data from Roberts and Lockett, 1978) and *Polygonum aviculare* (\circ) where dormancy is overcome during late autumn and winter and reintroduced in spring (data from Courtney, 1968):
 (a) germination of seeds extracted and tested in the laboratory under alternating temperature and light
 (b) diagrammatic representation of patterns of dormancy—seeds viable but fail to germinate in favourable conditions (unshaded areas), and seeds capable of germinating in favourable conditions (shaded areas); horizontal bars depict period of seedling emergence in the field (Karssen, 1980/81)

implicated, whereas high temperatures are responsible for after-ripening and breaking of dormancy in some winter annuals (Baskin and Baskin, 1980; 1981). Often a combination of interacting environmental conditions, such as temperature and light, is required to break dormancy. Furthermore, seeds exposed to these cues at the wrong time, at different levels or in the wrong combination may undergo induction to other forms of dormancy, or if in a labile state, may have dormancy reinstated.

Seeds with coat-imposed dormancy may fail to germinate because of chemical inhibitors in the coat, because the coat acts as a physical barrier to expansion of the embryo or because it affects water and/or gaseous exchange. Damage, erosion or decay of the seed coat generally alleviates dormancy. Seeds buried near the soil surface, where climatic conditions usually fluctuate more than at depth, undergo change more rapidly due to faster weathering.

Although considerable physiological detail is known about dormancy and its control (see, for example, Khan, 1982; Bewley and Black, 1983) there are as yet few practical ways open to utilise

this knowledge. Consequently the many applied avenues explored for terminating dormancy have to date met with only partial success (Egley, 1983).

Germination and seedling emergence

Germination is the animation of seeds and signals the start of a new life cycle. The manifestation of buried seeds into seedlings represents emergence, which strictly should be divorced from processes to do with the seed bank. But so often emergence is equated with germination because it is more easily observed in the field. There is both a time delay and considerable potential for mortality between the events of germination and emergence; neither should be overlooked when considering these processes. A further difficulty in interpreting germination behaviour is to distinguish between factors affecting germination *per se* and those concerned with breaking dormancy. Often the link is inextricable since conditions that terminate dormancy may also be conducive to germination.

Once seeds are released from dormancy they may germinate given favourable environmental conditions. It is not uncommon therefore to observe regular flushes of germination and emergence that are related to seasonal climatic conditions. For individual species these patterns are generally consistent from year to year, but a number of factors can influence this. The climate prevailing at the time of seed maturation influences the subsequent pattern of germination and emergence by 'preconditioning' seeds to respond to a sequence of environmental events.

The more important factors known to influence germination are temperature, oxygen and carbon dioxide concentration, light, moisture and chemical stimulants or inhibitors. All of these factors may vary within a soil profile, and germination may be prevented by one or more of them being unfavourable. Baskin and Baskin (1985) concluded that seeds of *Rumex crispus* (curly dock), a species having no form of seed dormancy, survived when buried in soil purely because light and temperature conditions were unfavourable for germination. In other species seeds may become dormant or resume a dormant state if conditions are unfavourable. This is evident in *Aphanes arvensis* (parsley piert) (Figure 9.4), where dormancy is controlled by temperature. Seeds that had been released from dormancy all germinated given favourable temperatures (constant 4°C or alternating 4/10°C). At other temperatures germination was incomplete and at constant 25°C seeds completely failed to germinate (Roberts and Neilson, 1982). Because the other environmental factors controlling dormancy and germination are likely to act in the same variable manner, the permutations of conditions that partially or wholly affect dormancy, and subsequently germination, are infinite. This could explain why mostly only a small proportion of seeds in the soil emerge annually. It is not uncommon for annual emergence to be less than 10% of the viable seed bank (Roberts, 1981; 1984), and sometimes less than 1 to 2% (Roberts and Ricketts, 1979).

Emergence is least from deeply buried seeds and greatest from seeds near the surface in their first year of burial. Soil disturbance through cultivation also increases emergence (Figure 9.5), and the over-riding influence of rainfall on emergence is also evident. In the example illustrated by Figure 9.5, emergence was greatest immediately after rainfall while the timing of tillage had little influence. For instance, cultivation in early summer stimulated little immediate emergence; the main flush of emergence did not occur until late summer following four rainfall events of 10 mm or more. After the initial flush of emergence, the rate of appearance of further seedlings was similar with or without cultivation. Details of the species composition of cohorts emerging following different times of cultivation, and reasons for the varying magnitude of emergence flushes in the above example are discussed by Roberts (1984).

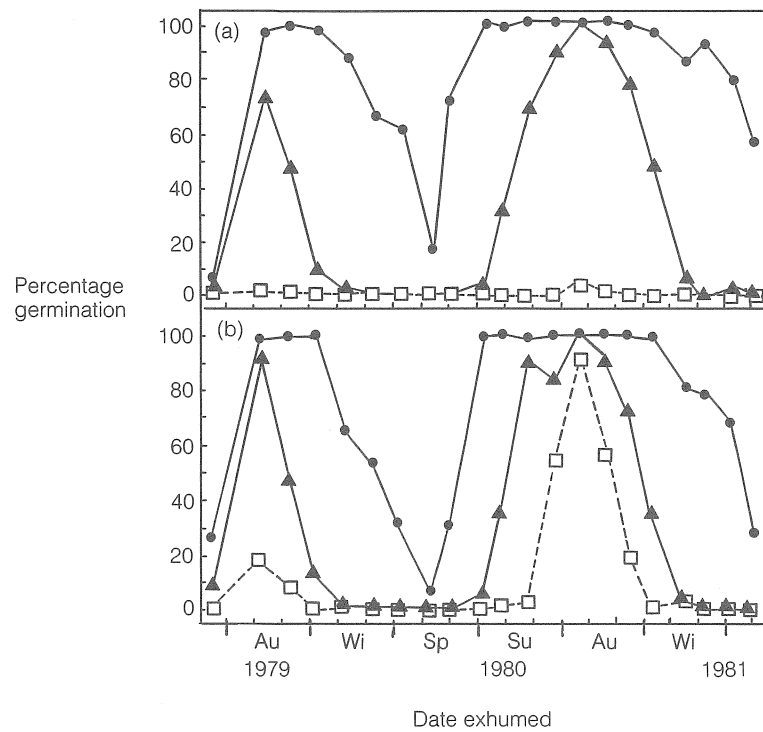


Figure 9.4 Changes in the state of dormancy of buried seeds of *Aphanes arvensis* after extraction over time and germinated at:
 (a) constant temperatures of 4°C (●), 15°C (▲) and 25°C (□);
 (b) alternating temperatures of 4/10°C (●), 10/20°C (▲) and 15/30°C (□) (Roberts and Neilson, 1982)

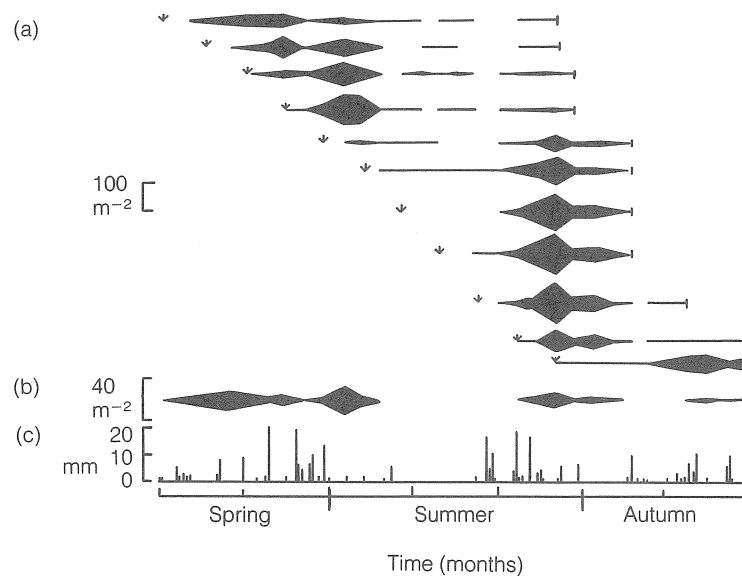


Figure 9.5 Weed-seedling emergence (a) following tillage at 2-week intervals and (b) when not cultivated; (c) shows daily rainfall. Arrows indicate date of cultivation, and vertical lines indicate when recording ceased (Roberts, 1984)

The reasons for the effect of cultivation on weed seed emergence are not clear. One possibility is that buried seeds are released from dormancy, e.g. photoblastic seeds may receive sufficient light during tillage to break dormancy. Another more general reason is that tillage increases the number of habitats within the profile that are suitable for germination and emergence. This could explain the interaction of rainfall and tillage outlined above since structural changes in the arable layer resulting from tillage would provide improved water relations generally as well as specifically around seeds due to better seed-soil contact.

'Decay' of seed banks

Seeds of many annual species remain viable in the soil for decades, while others are short-lived. Thompson and Grime (1979) classified four types of persistence in seed banks; types one and two have no carryover of seed from year to year so seeds persist only long enough to re-establish a population; in the other two categories seeds persist in varying numbers and typify the behaviour of most arable weeds. Persistence of a seed in the soil depends primarily on the control of germination, the major factor causing loss of seeds from a buried population (see below). Other losses are due to the removal (export) of seeds through the action of wind, water and animals, and death due to rotting, predation or metabolic failure. The sum of these fates over time produces a 'decay' curve, the slope of which is an expression of the seed-to-seed variation (see Roberts and Ellis, 1982 for detail).

The general indication from European and North American research is that seeds in the cultivated layer of arable soils decay at an exponential rate, but the exponent value varies for different species and 'storage' conditions (Roberts, 1970; Roberts and Feast, 1973a,b; Roberts and Neilson, 1980; Egley and Chandler, 1983). However Burnside *et al.* (1981) found a hyperbolic model better described the decay of seed banks of 10 species buried in soil containers located in the field. The rate of decay can be considerably increased by tillage; frequent tillage increases decay (Roberts, 1970) but the timing of tillage has less effect (Roberts and Potter, 1980; Roberts, 1984) (see also Figure 9.5). This indicates that decay resulting from tillage is probably attributable to germination. Type of tillage can also be important. For example, seed bank decay of *A. fatua* was greater with tine cultivation than with ploughing (Wilson, 1978; 1985) but the decay of *Alopecurus myosuroides* was similar in many types of cultivation and grass leys (Moss, 1985). In contrast, Warnes and Anderson (1984) found that seed of *Brassica kaber* (charlock) lost viability more slowly under a grass ley than where the soil was tilled three times each year. Species with hard seed coats decay more slowly (Roberts and Neilson, 1980) than species with seeds that are less dormant initially. For example, 25% of seeds of *Chenopodium album* remained after 6 years, whereas only 12% of seeds of *Poa annua* survived (averaged over three depths of burial in disturbed and undisturbed soils) (Roberts and Feast, 1972). Lewis (1973) concluded that seeds of few grass species persist longer than 4 years; 1% of *A. myosuroides* seed populations buried in several ecosystems remained after 4 years (Moss, 1985). Populations of *A. fatua* having different dormancies, but lacking innate embryo dormancy, persisted less than 2 years regardless of depth of burial (Zorner *et al.*, 1984a). In other studies, 5% of one *A. fatua* population was still viable after 4 years (Wilson, 1985), while 1% of another population persisted after 7 years (Banting, 1966), both apparently due to embryo dormancy.

Death of seedlings between germination and emergence ('fatal' germination) may account for the small number of seedlings that emerge compared with the total seed bank. For example, more than half the seeds of *A. fatua* buried at a depth of 75 mm and almost all seeds buried at 230 mm that germinated, failed to produce seedlings (Murdoch, 1983). Zorner *et al.* (1984a) found that deeply buried seeds of *A. fatua* were more likely to germinate compared with seeds at shallow depths.

However, seeds closer to the surface tended to lose viability more rapidly, possibly due to metabolic failure. Wilson (1985) could not account for the loss of more than 85% of buried seeds of *A. fatua* - but they may have been lost through fatal germination. While the roles of predation, rotting, death and export cannot be dismissed in this context, fatal germination appears to contribute more to seed bank decay.

Deeply buried seeds generally remain viable for a longer period than ones on or near the surface. For example, seeds of *Achillea millefolium* (yarrow), which are positively photoblastic, lost viability more slowly when buried (Kannangara and Field, 1985). However, this does not always hold for species having only short-term dormancy, as shown with *Bromus sterilis* (sterile brome), where deep burial resulted in extinction of the seed bank (Froud-Williams, 1983) along similar lines to that discussed above for *A. fatua*. In other cases where viability is maintained at depth (even if dormancy is not involved), upheaval of seeds reinstates their availability for seedling recruitment (e.g. non-dormant seeds of *R. crispus* (Baskin and Baskin, 1985) cf. dormant seeds of *R. raphanistrum* (Reeves *et al.*, 1981)). The interaction of seed decay with depth of burial is further illustrated in *Kochia scoparia* (kochia) (Zorner *et al.*, 1984b) and *Striga asiatica* (witchweed) (Bebawi *et al.*, 1984). Egley and Chandler (1983) found depth of burial had little effect on seed decay of 20 species mixed with sandy loam and buried in a well-drained silty clay loam soil sown to turf.

The method used to manage stubble may also influence seed longevity. For some annual grass weeds there appears to be an advantage in removing stubble by burning. For example, seeds of *A. fatua* (Wilson and Cussans, 1978) and of *A. myosuroides* (Moss, 1980) lying on the surface can be killed, especially by burns that produce high temperatures near the surface. The effect depends, among other factors, on the amount of stubble, the speed of the fire and the moisture content of the seed. Imbibed seeds and those covered by even shallow layers of soil suffered less damage but were stimulated to germinate. The fire residues appeared to provide a favourable seedbed which also enhanced germination.

REPRODUCTION

Weeds could be easily eliminated if they did not reproduce. If this were the case the time required to eradicate a species would be directly related to the rate of seed bank decay. In practice, however, some plants survive or escape treatment during a crop. These produce propagules, which are either dispersed into the seed bank or exported from the field in some way. Mostly, the numbers of seeds returned to the soil are large (Leguizamón and Roberts, 1982). In the case of *A. myosuroides* this is because most new seeds are shed before harvest (Moss, 1983). *A. fatua* likewise commonly matures and disperses prior to crop harvest and its persistence as a weed of arable land has been attributed more to the reproduction of survivors than to longevity of seeds in the soil (Wilson, 1978).

The fecundity of weeds varies from a few seeds to several hundred per plant and, like crop plants, is density dependent. For example, Radford *et al.* (1980), using a mixed population of *Avena* spp. (wild oats), found that seed production per unit area was similar for all weed densities at low crop density (Figure 9.6). However, weed seed production declined as crop density increased, especially at low weed populations. Seed production of *L. rigidum* seemed less plastic and remained high over a wide range of densities with mixtures of wheat (Rerkasem *et al.*, 1980). Time of emergence, soil moisture and fertility are other factors that influence weed fecundity (Peters, 1982b; O'Donovan and Sharma, 1983).

Seed production can also vary among plant ecotypes. For instance, the date of flowering and seed

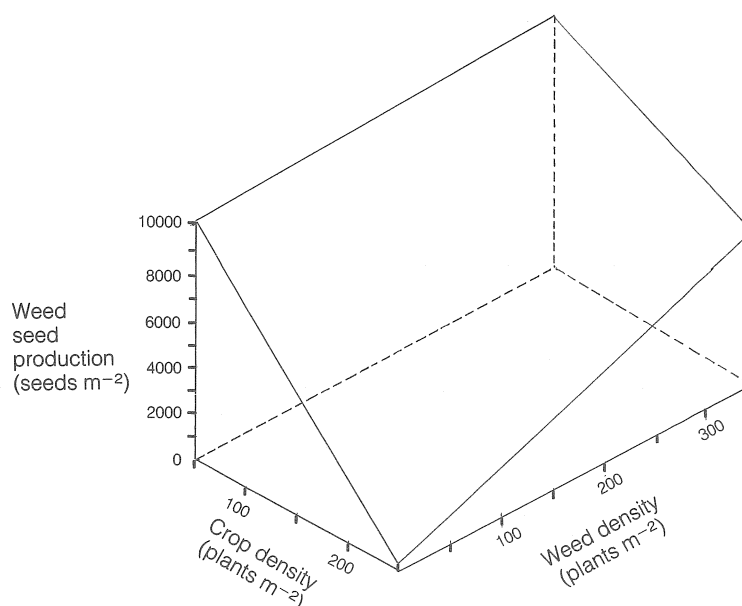


Figure 9.6 Effect of wheat density on seed production of *Avena fatua* grown at a range of densities (adapted from Radford *et al.*, 1980); (data for 1971 and 1973 used for fitting the response surface, $Y = 10738 - 0.64 Z - 51.58 X + 0.09 ZX$ [$r^2 = 0.57$] where Y = weed seed production, X = density of crop and Z = weed density)

production per plant differed between southern and northern ecotypes of *Cassia obtusifolia* (sicklepod) (Retzinger, 1984). Moss (1983) found also that viability of early and late produced seed of *A. myosuroides* was lower than that of seed disseminated during the peak shedding period.

While studies of seed bank losses and inputs from reproduction have contributed a general knowledge of the behavioural pattern of seed banks, they have not clearly identified the effects of different tillage systems. This knowledge is consequently of limited value for deciding how management tactics such as the type and frequency of tillage, sowing time, herbicide choice and application time can be used to obtain maximum effect on seed bank decay (e.g. Wilson *et al.*, 1985). Because it is not possible to precisely identify the specific conditions that regulate seeds, the basis for predicting the fate of seeds is tenuous. The inability to identify conditions favouring germination, seed death, maintenance of dormancy or resumption of dormancy makes it difficult to generalise about the effects of tillage on buried seeds and to conceive of ways to alter environments to manipulate buried seeds in the field. Understanding seed behaviour so that practical methods of exhausting seed banks can be developed remains a major challenge to weed science. Emphasis should be placed on persistent species with seeds that 'decay' slowly.

MANAGEMENT OF WEED POPULATIONS

Regardless of the type of crop being produced, the control of weeds forms an integral part of almost every operation in both the preparation of a field and during the subsequent production of the crop. In both the preparation and production phases of a crop cycle, weeds can be directly controlled by intervening to apply specific treatments or they may be indirectly

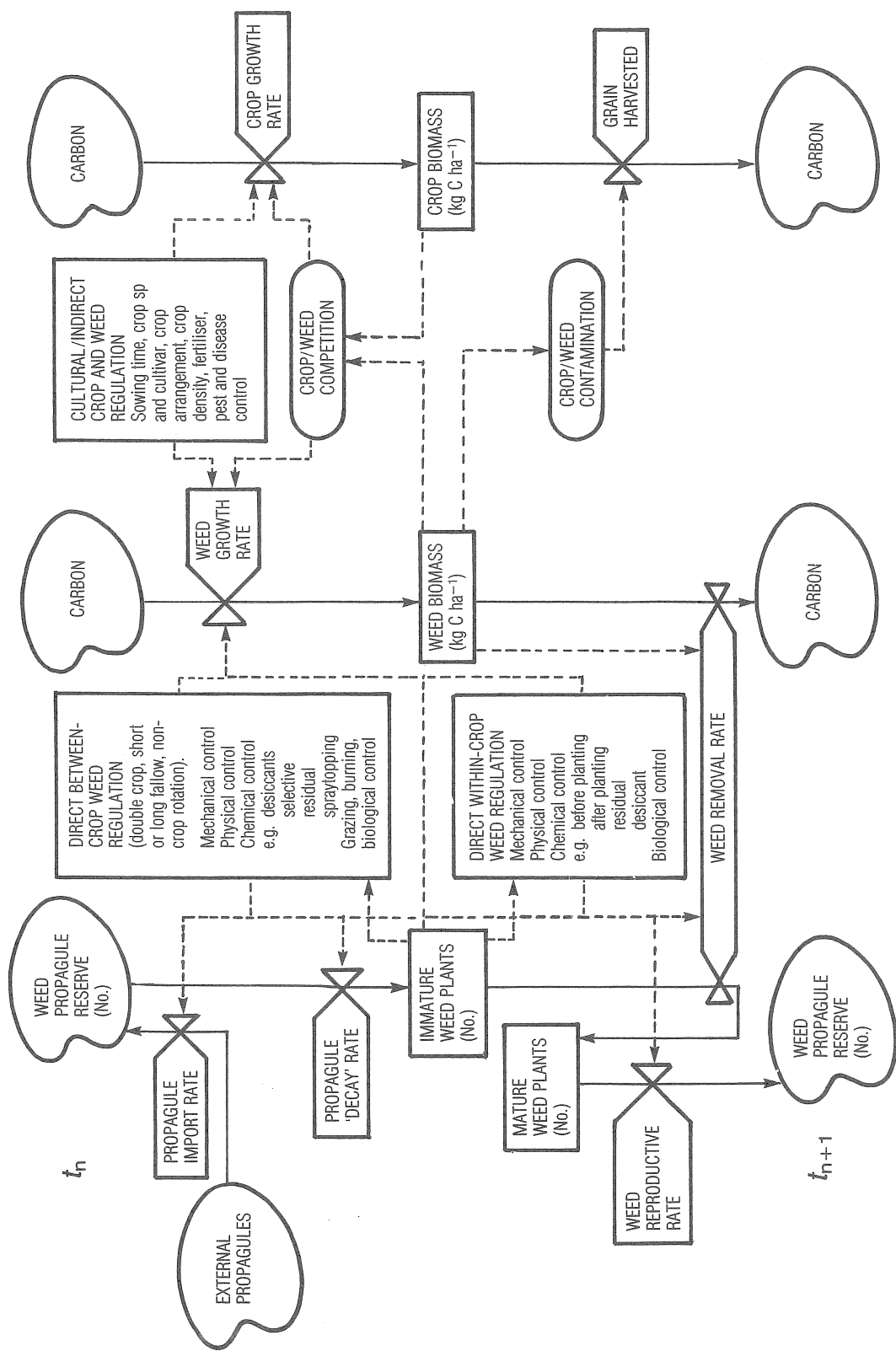


Figure 9.7 Generalised diagrammatic model of weed management in crops

suppressed by cultural means, i.e. by adopting sound crop husbandry practices. The inter-relationship of these phases and tactics are illustrated diagrammatically in Figure 9.7.

WEED CONTROL IN THE CROP

Indirect control

Weeds can be suppressed by adopting crop husbandry procedures that produce vigorous crops and which maximise their ability to compete with weeds. However, the powerful influence of direct control using herbicides has, to a degree, overshadowed the importance of crop husbandry in weed management. In this context it is worth noting that crop agronomy recommendations are commonly assembled from results obtained in near weed free experimentation. The justification for this is that weeds can be controlled by direct treatment if they are a problem (i.e. by the application of herbicides or some other means) - a somewhat circular argument. The combination of sowing time, crop genotype, crop planting arrangement, crop density and fertiliser input that is optimal under weed free circumstances, is not necessarily optimal in weedy fields (Snaydon, 1982; Spitters and van den Bergh, 1982). Moreover, a desirable assemblage of husbandry practices can contribute considerably to weed control at very little extra cost.

Genotype

Not only do weed species have different competitive powers (Welbank, 1963; Wells, 1979) but crops themselves have different competitive abilities, as previously discussed in relation to weed floras.

An example of the ability of four winter crops to compete with weeds showed that barley was least affected by *A. fatua*, followed by rapeseed, wheat and linseed (Figure 9.8) (Dew, 1978, cited by O'Donovan and Sharma, 1983). Furthermore, different cultivars of a crop may compete differently with weeds (Reeves and Brooke, 1977; Gates *et al.*, 1981; Henson and Jordan, 1982). The rates of seedling root growth and leaf emergence (which are generally greater for larger seeds), leaf arrangement and tillering behaviour may all engender such genotypic variation.

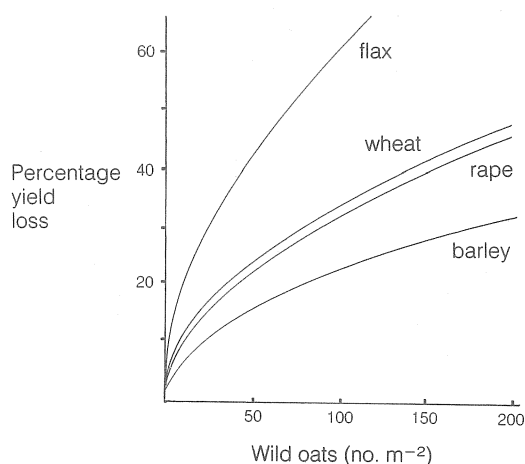


Figure 9.8 Influence of the density of *Avena fatua* on yield loss in four crops (Dew, 1978 as cited by O'Donovan and Sharma, 1983)

In general, however, the reasons for the different competitive abilities of crops have been inadequately studied, although maximising the genetic potential of crops to suppress weeds remains an attractive possibility.

Crop density and arrangement

Increasing the density of crops can reduce competition from weeds (e.g. Felton, 1976; Radford *et al.*, 1980; Lawson, 1983; Carlson and Hill, 1985; Medd *et al.*, 1985). In dryland wheat, maximum yields can be achieved over a wide range of densities in weed free conditions (Auld *et al.*, 1983). However, there is a risk of yield loss in dry seasons if plant density is too high (Fawcett, 1964) although this appears less of a concern in soils that have a greater water-holding capacity (Radford *et al.*, 1980; Thomas *et al.*, 1981). Crop density is thus a difficult parameter to specify but, as advocated for wheat (Martin and McMillan, 1984), populations higher than those normally recommended should be considered in fields with a history of weed problems.

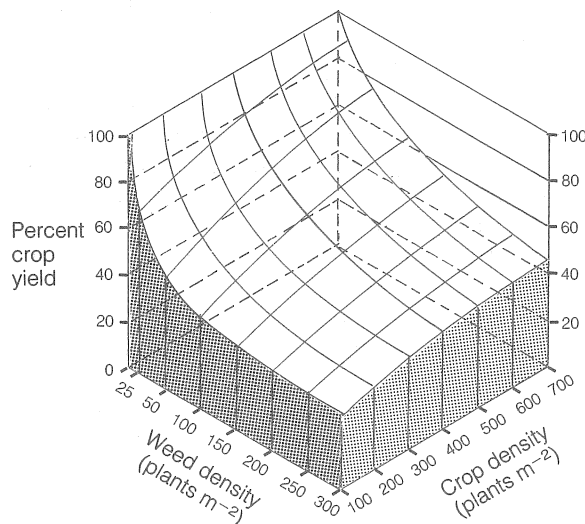


Figure 9.9 Interaction effect of the density of crop (wheat) and weed (*Avena fatua*) on crop yield (%) relative to weed-free crop (Carlson and Hill, 1985)

Sowing rates should always allow for establishment failures as well as taking into account individual seed weight and viability, since quality varies between seed batches. Failure to correctly adjust the sowing rate results in a sub-optimal population density. Use of the population density concept has been accepted for several recently developed crop species in Australia, particularly those grown under irrigation, and should be adopted *in lieu* of sowing rate for all crops.

The planting arrangement of a crop also affects how it will resist competition from weeds (Fischer and Miles, 1973; Felton, 1976; Holland and McNamara, 1982; Medd *et al.*, 1985). Within the limits of crop density, in general, plants that are uniformly spaced are better able to compete with weeds. This applies less strictly to freely tillering crops such as wheat grown without irrigation (Medd *et al.*, 1985). In some vegetable crops a narrowing of row spacing shortened the period during which crops could remain infested before suffering reduced yields (Weaver, 1984).

Emergence

Time and speed of emergence influence the competitive interactions of crops and weeds. Both weeds and crops that emerge rapidly are respectively likely to be more competitive. In crops

that tiller, yield potential is set during early vegetative growth since the number of seed heads (fertile tillers) is a primary component of yield. Stress during early growth, including competition from weeds, reduces tillering which in turn can reduce yield. It is important therefore to control weeds early in the life of such crops before competition causes irreversible potential yield loss. For example, Peters (1984) showed that early emerging plants of *A. fatua* competed more severely with spring barley than did later emerging plants. Furthermore, when plants that emerged early were removed from the crop just prior to the emergence of later plants, the later emerged plants failed to compensate and did not significantly affect yield. Forcella (1984a) found that early established plants of *Vulpia* spp. (silver grass) were larger and contributed more to total population weight (and probably also to competition with the crop) than did later establishing plants. Plants of *A. myosuroides* that germinated early had a greater competitive effect on winter wheat yield due to below-ground interference (Snaydon, 1982). Seed size can influence the vigour of plants, and with *A. fatua*, plants derived from large seeds competed more severely with barley than did those from smaller seeds, especially when emerging from deeper within the soil (Peters, 1985). On the other hand, Soetono and Donald (1980) demonstrated the superior productivity of barley plants that established quickly; slower establishing plants were more liable to yield fewer grains. Knight (1983) found that wheat plants that emerged 5 days after sowing yielded three times more than plants that emerged on day 12 and the size and proximity of neighbours further affected the yield of plants. Speed of emergence and leaf and root development are among the factors that influence a crop genotype's ability to compete. All of these are affected by climate (see Evans *et al.*, 1975), soil fertility and control of insect pests and diseases.

The tardy initial development of direct drilled crops (Greenwood *et al.*, 1970; Gates *et al.*, 1981) may give early establishing weeds a competitive advantage. Similarly, deep sowing, soil crusting or low soil moisture may reduce the rate of crop emergence. Mulching and water injection are possible practices for sowing into dry seedbeds (Radford and Nielsen, 1983), which allow earlier sowing and possibly favour more rapid crop emergence while suppressing weed emergence. Soil temperature also affects emergence, particularly of summer crops. Emergence of grain sorghum is especially sensitive to low temperatures (Launders, 1971). Poor establishment resulting from premature sowing can lead to increased weed infestations. Phytotoxins in weed and crop residues can also affect emergence and seedling performance by reducing early crop root and/or shoot growth (Kloot and Boyce, 1982; Lovett and Jessop, 1982; Levitt and Lovett, 1984).

Time of sowing

Delayed sowing of crops can sometimes assist in the control of weeds. Where the pre-sowing period has been dry, little weed emergence occurs. If the crop is sown immediately after opening rains it is liable to coincide with a flush of weed emergence. Thus, there may be a case for allowing weeds to emerge before beginning to sow, a possibility mentioned by Kohn *et al.* (1966) in relation to direct drilled wheat. This is a complex topic, since delayed sowing may result in lower yields depending on the length of delay and the availability of cultivars suitable for late sowing (Evans *et al.*, 1975; Hanks and Puckridge, 1980; McDonald *et al.*, 1983; Woodruff, 1983). But perhaps more importantly, a delay can increase the risk of being unable to sow if rain persists. In terms of weed seed biology, the expectation is for less than 10% of seeds to emerge annually and a majority of these do so in an initial flush when soil moisture is plentiful (Figure 9.5). Cultivation of land prior to sowing can increase the magnitude of this flush. Control of these weeds before introducing the crop has traditionally reduced dependence on in-crop control measures, and/or improved the efficacy of such measures. The conventional seed drill with its scarifier action was designed specifically for this function. This is essentially the role also of cultivating a month or so before sowing in reduced cultivation

methods, the use of pre-emergence herbicides, and of desiccant or knock-down chemicals immediately before sowing in direct drilled crops. In all cases, it could be advantageous to delay sowing until the initial flush of weed emergence occurs. However, delayed sowing is not a useful tactic against weed species with prolonged emergence patterns since competition can be more intense in late sown crops, as shown for *L. rigidum* (Reeves, 1976). Such conflicts arise also in direct sowing systems where the absence of prior cultivation eliminates the possibility to evoke weed emergence and where crop establishment is tardy.

Nutrition

Nutritional deficiencies during early crop growth may slow growth of the crop and allow weeds more opportunity to exploit the available resources. For example, Gates *et al.* (1981) found that direct drilled crops were phosphorus and nitrogen deficient during early development. However, equivalent yields could be obtained on cultivated seedbeds and with direct drilling provided weeds were controlled and additional fertiliser applied. Peters (1984) found that nitrogen applied at the three- to four-leaf stage enabled spring barley crops to completely compensate for the competitive effects of *A. fatua* plants present in the crop until the four- to five-leaf stage. This indicated that time of fertiliser application should also be considered as a way of offsetting the effects of early weed competition. Forcella (1984b) concluded that if mixtures of wheat and *L. rigidum* are not supplied with adequate nitrogen in early phases of crop growth, the weed may predominate. Wheat competed effectively with *L. rigidum* for nitrogen up to the three-leaf stage but between four and six leaves was inferior to *L. rigidum*. Similarly, Barrett and Campbell (1973) demonstrated that wheat competed better than *L. rigidum* for nitrogen and light up to late tillering, especially at high crop densities. However, if weeds compete more efficiently than the crop for nutrients during establishment, high levels of nutrition will exacerbate weed competition. For example, it is uncommon for broadleaf weeds to be repressed by the addition of nitrogen, even though the crop may benefit (Wells, 1979). While the placement of fertiliser within the soil profile may not be important for wheat production (see Alston, 1980), there may be a case for adjusting fertiliser placement to disfavour early weed growth.

Direct control

The main objective of direct intervention to control weeds in a crop using physical, mechanical or chemical means is to remove competitive stress and to reduce the reproductive output of the weed population. Physical and mechanical methods of control are rarely feasible in broadacre cropping but still have a role in intensive high-value crops and in row cropping. With physical and mechanical methods the degree of selectivity depends on operator skill. All weed species will be affected, as will the crop if operations are carelessly undertaken. Chemical methods are to a degree both weed and crop selective so ideally only target species are affected. The susceptibility of weed species varies widely; some chemicals may be specific to species, genera or families. Several recently developed chemicals have activity across a much broader spectrum of species and many proprietary mixtures as well as registered 'tank mixes' of chemicals can be used to ensure broad-spectrum activity. Rarely is crop selectivity absolute (Hawton, 1980) and crop damage is avoided or minimised by an interplay of herbicide concentration, the timing of applications to coincide with tolerant crop growth stages, and by avoiding cultivars with lower tolerance (Lemerle, 1984).

Disregarding economic matters, the use of chemicals for in-crop weed control comes down to choosing the herbicide(s) best suited to the crop species and stage of growth, environment, available application equipment and target weeds. The choice will not always be the cheapest

alternative since a more expensive chemical may give a better result. Similarly, a better result may ensue from using a higher dose of a particular chemical. In order to obtain a desired spectrum of activity the choice of chemicals may be limited by compatibility. For example, antagonism occurred when 3,6-dichloropicolinic acid was mixed with barban or Mataven but not with Avenge or Hoegrass (O'Sullivan and Kirkland, 1984). Higher levels of straw residues in reduced cultivation systems may reduce the activity of some herbicides, as can high levels of ash if the residues are burnt (Pollard *et al.*, 1982). This may necessitate the use of higher doses or of more expensive alternatives. Chemicals with residual properties, e.g. atrazine, may be undesirable where sensitive crops are to follow in a rotation. Other chemicals that are prone to drift away from the target area are also unsuitable if sensitive crops occur nearby (Gilbey *et al.*, 1984). Manuals published by the State Departments of Agriculture (e.g. Dale, 1984/85; Gammie and Dellow, 1986) and by Swarbrick (1984) provide listings of registered formulations and usage guidelines. Further technical advice to assist with the choice and use of chemicals is readily available from commercial and governmental advisory services. Having chosen the chemical, its efficacy will depend among other things on how thoroughly the chemical is applied to the target, the condition of the target (stressed or otherwise) and the climatic conditions prevailing at the time of and following application. The application of herbicides is discussed in detail in Chapter 10.

Generally, the earlier a chemical is applied, the greater will be its efficacy since susceptibility is highest in young actively growing targets. Because young weeds are more susceptible, lower doses of herbicides may suffice so that savings can be made by applying herbicides early. Also, as discussed previously, the longer weeds are permitted to compete with the crop the greater will be the damage (see Spitters and van den Bergh (1982); and Snaydon (1982)). The 'critical period' of competition denotes the optimum timing of weed removal to prevent potential yield loss (Weaver, 1984). For weeds with prolonged emergence patterns (e.g. *L. rigidum*), treatment is best delayed to minimise residual weed populations when these compete with the crop or contribute significantly to weed seed production. Chemicals with prolonged activity are useful in this context.

In addition to economic decisions (considered below), which influence whether or not to apply a herbicide, producers are often faced with unfavourable seasonal circumstances, which require careful adjustment to in-crop weed control plans. If crops are established on soils with a meagre soil water store and the season remains dry, the question arises as to whether further funds for weed control should be invested in the crop. In mixed farming enterprises such crops may be grazed or conserved as fodder in order to recoup expenditure to that point. Other alternatives are to proceed with weed control or delay or abandon further inputs. If delayed, the crop may advance beyond the tolerant growth stage (given favourable rainfall) preventing the use of many herbicides because of the increased risk of phytotoxicity to the crop. Protracted wet or windy conditions can also delay spray application schedules. Disruption of treatment along these lines can lead to crops being more heavily infested than would normally be tolerable and these infestations result in both high yield losses and considerable replenishment of weed seed banks.

WEED MANAGEMENT BETWEEN CROPS

The period between crops may vary from days to years. Regardless of the non-crop period, management of weeds is no less important between crops than it is within crops because:

- * weeds transpire and deplete soil water reserves;

- * weed growth can slow the operation of machinery and increase costs of land preparation;
- * if unchecked between crops, they will reproduce and add to the seed bank;
- * they act as reservoirs of crop diseases - this applies especially to annual grasses that host diseases such as cereal cyst nematode and *Rhizoctonia* (Chapter 14).

For these reasons management between crops should aim to minimise weed biomass, prevent reproduction, and enhance the decline of populations by increasing the rate of 'decay' of seed banks. Where conservation of soil water or reduction in disease inoculum potential are major between-crop priorities, all three management objectives apply. In other cases it is less important to control weed biomass other than for the purpose of stopping seed production.

Cultivation has been a traditional method of killing weeds. The choice of implement and timing of cultivation is dictated largely by the amount of biomass present and the penetrability of the soil. The implement, however, does have a profound bearing on the effect cultivation has on the seed bank. If the objective is to deeply bury seed then mouldboard or disc ploughing is necessary to invert the sod. Deep burial, particularly of seeds of many annual grasses that lack long-term dormancy mechanisms, enhances decay of seed banks. However, deep ploughing with disc or mouldboard implements is slow and costly so ploughing of portion of a field on a rotational plan may be a useful tactic. Seeds having greater longevity can be treated likewise, but they will probably survive (see above) and be reintroduced into the labile seed pool with any subsequent deep ploughing. Shallow cultivation or, ideally, grazing together with direct drilling in the intervening years complements this tactic by minimising the chance of reinversion. This method is especially suited to fields coming out of a pasture rotation. However, the benefits of deep burial would not be fully realised if further seeding occurred after ploughing, placing increased importance on preventing reproduction both between and within crops.

Alternatively, if weeds are permitted to seed or if deep inversion has not been used, shallow cultivation and possibly the burning of stubble will enhance the rate of 'decay' of newly deposited seed, but have less effect on existing seeds in the soil. Seeds near the surface have a higher probability of natural wastage, and mortality and emergence can be enhanced by cultivation and stubble burning (see earlier). In the case of tillage, these events are repeated due to emergence brought about by disturbance associated with each cultivation cycle. A single cultivation suffices if weeds emerge synchronously, e.g. *Brassica tournefortii* (Amor, 1985). However, many species tested in Amor's study had prolonged emergence and did not respond to a single cultivation, e.g. *A. fatua*, *Lamium amplexicaule* (deadnettle) and *Phalaris paradoxa* (paradoxa grass). Amor concluded that if zero tillage replaced conventional cultivation, the incidence of these weeds would be little altered. If emergence of these weeds was enhanced by **multiple** cultivation then seed banks would be reduced, as would probably be the need for in-crop control. It seems, therefore, that the reduced opportunity to manipulate seed banks in zero tillage or direct drill systems will inevitably require greater inputs to in-crop weed control. This could be exacerbated by the lack of interspecific competition of direct drilled crops due to their slow initial growth rates. It might also be foreshadowed that weeds having prolonged emergence patterns will dominate such tillage systems.

Clearly, if emergence is stimulated, a number of options can be adopted to subsequently kill the emerged seedlings, depending on the tillage system employed. These include further cultivation, the application of pre-plant or incorporation of pre-emergence herbicides or the use of a traditional seed drill.

The use of knock-down and residual herbicides to kill weeds in fallows has become widespread due to the growing adoption of conservation farming techniques. Apart from carefully evaluating the cost/effectiveness of cultivation versus herbicides, there is a vital need when using residual chemicals to plan crop rotations. Herbicide concentrations sufficient to damage sensitive crops may remain in some soils for several seasons (Hance, 1984). Reflectance detectors, which are able to sense and limit the application of chemicals to growing targets, are available (Haggard *et al.*, 1984). Avoiding the unnecessary spraying of herbicides onto bare areas of the fallow has the dual benefits of reducing costs and the likelihood of residual activity.

The build-up of weeds in continuous cropping frequently necessitates a change in land use, either by rotating with a break crop or by sowing the field to pasture. Use of a break crop permits rotation of herbicides. For example, if annual grass weeds became a problem in winter cereals, production could shift to a winter legume or an oilseed crop that is tolerant of grass-active herbicides. Another option is to rotate crops having different growing seasons. For example, a build-up of *Avena* spp. in winter crops was reduced by almost 97% by growing sorghum over summer, allowing the weed to be controlled in a winter fallow (Philpotts, 1975). The critical action is control of the weed over winter so there would be little benefit if opportunistic double cropping was practised. In either rotational case, the choice of a leguminous break crop has the added benefit of improving soil nitrogen content.

Annual grass-legume pastures are widely used in rotations and may also improve soil fertility. Often plants that are tolerated in pastures, such as *H. leporinum* and *L. rigidum*, are major crop weeds. Mismanagement of these species by allowing them to seed in the pasture will greatly contribute to their presence in the following cropping phase. Again, several options are open to manage pastures. Plants can be 'crash' grazed to prevent seed head formation (e.g. Myers and Squires, 1970). Slashing, cutting for fodder conservation, or the application of herbicides to kill plants or prevent seed head formation are other possibilities. Combinations of spraying and grazing are also possible, e.g. spray-graze (Pearce, 1972) and pasture topping followed by grazing (Jones *et al.*, 1984). Management to control seeding of potential crop weeds during a pasture phase is especially beneficial in the year prior to returning to cropping (see Chapter 5 for more detailed discussion). Its main benefit stems from considerably reducing the need for subsequent in-crop control.

WEED MANAGEMENT ECONOMICS

IN-CROP COMPETITION LOSSES AND CONTROL COSTS

Profitability of cropping is reduced by weeds due primarily to yield losses incurred through competition. This is often the sole motivating reason for expenditure on weed control. In order to decide how much to spend on controlling weeds it is first necessary to forecast the likely loss of crop yield.

The basic model used for describing this loss of yield due to weed competition is the yield loss - weed density function. Cousens *et al.* (1984) have shown that a hyperbolic model adequately describes loss of crop yield (relative to weed free yield) in relation to weed density (Figure 9.10). The model is biologically reasonable since yield loss is zero in weed free crops (so the curve is forced through the origin) and loss approaches the upper limit (100%) in an asymptotic manner. The impact of weeds at low density tends to be larger (and of a linear nature) than of

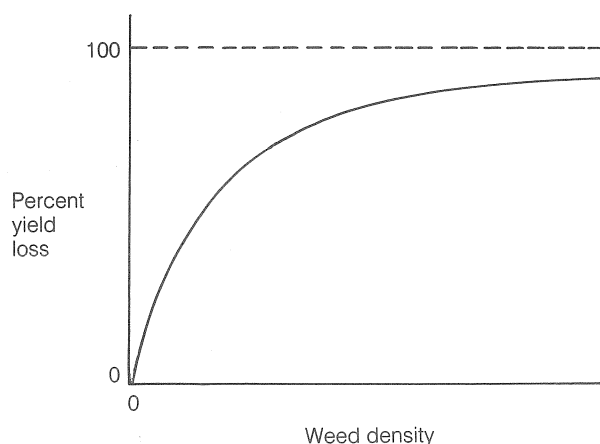


Figure 9.10 Idealised yield loss—weed density model used to describe losses due to weed competition in crops (Cousens *et al.*, 1984)

weeds at high density (imparting curvilinearity) since the inter-specific competitive effects reduce the incremental yield loss as weed density increases (Tisdell *et al.*, 1984).

Many models of weed-crop competition use weed density as the independent variable (Spitters and van den Berg, 1982), or some transformation of density such as its square root (Dew, 1972). Use of density as a parameter has undoubtedly been favoured because it is easily measured. Yet there is increasing evidence that weed biomass, not density, better represents the outcome of interacting effects of weeds with themselves and with the crops (Chisaka, 1966; Noda *et al.*, 1968; Topham and Lawson, 1982; Wilson and Peters, 1982; Lawson and Topham, 1985; Medd *et al.*, 1985). The latter work showed that weed density alone is not a satisfactory predictor of the outcome of competition since final weed biomass is plastic and is only partially related to weed density in competing mixtures.

While weed biomass (at crop maturity) correlates closely with yield loss, it is impractical for forecasting since it cannot be easily predetermined. Medd *et al.* (1985) demonstrated, however, that the ratio of weed to crop density is a biologically reasonable parameter for predicting yield loss since it implies that reduction in crop yield is proportional to the relative reduction in biological space.

The ultimate use of loss curves is for deciding the level of infestation at which the value of the increased production expected from control equals the cost of treatment. This point is termed the economic threshold or critical infestation (density in many models). The point is primarily determined by the competitiveness of the weed (expressed as the slope of the curve) and the cost of treatment. Timing of treatment is also important since crops may be unable to compensate fully if weeds are controlled too late.

Maximum slope of the curve occurs near the origin so if the threshold lies in this zone, the loss function will effectively be linear, as Marra and Carlson (1983) have argued. The slope of the curve is increased if the weed is more competitive (factors influencing the vigour of weeds were discussed previously). Essentially, factors that modify the slope of the relationship can be considered as variation and expressed as a deviation band around a mean response (Chisaka, 1977). In general, the lower the cost of control the lower will be the level of infestation at which the threshold occurs (see Auld *et al.*, 1987, for more detail). In broadacre crops the cost of applying a treatment (but not necessarily the cost of ingredients in the case of chemicals) is mostly independent of the level of infestation. Costs can be reduced by techniques of low volume chemical application, and/or by using chemicals suitable for early post-emergence

application (where a lower dose is effective on younger weeds). However, when the effectiveness of a treatment declines, or where an increase in dose gives better control, the treatment cost increases and so the threshold will rise to higher levels of weed infestation if the treatment of more intense infestations takes longer to complete. When the treatment has a short effective life, re-treatment may be necessary for some problems to reduce damage from later emerging cohorts. Chemicals having an extended active life may be useful for such problems but are often more expensive and, as discussed above, their residual properties can reduce rotation options and encourage the appearance of resistant biotypes.

As outlined previously, most weed infestations consist of species mixtures, and treatments having activity on a broad range of species are required to minimise costs. Only the cost of ingredients are additive when several products can be mixed and applied as one. However, the costs of treating mixed infestations is increased if species-specific chemicals cannot be mixed and applied collectively. The idealised single species model therefore needs to be extended to describe yield loss in relation to the total weed population. Indices of weed species diversity (Topham and Lawson, 1982) may be useful in this context. Furthermore, the question of priority treatment of individual species in a mixed infestation appears not to have been considered yet but would be influenced by the relative abundance of each target and its contribution to total loss.

LONG-TERM CONSIDERATIONS

The economics of weed management systems should be considered not only in terms of current benefits but also in terms of future effects. While control may be uneconomic in the current year, treatment in the current year may prevent or delay the future build-up of populations and hence benefits need to be evaluated in the long-term. The dynamics of seed reserves are of particular importance in this context since they are a major source of re-invasion. Cousens (1986) therefore argued that the concept of current year economic threshold is **not** a useful tool where management allows seed reserves to accumulate and, furthermore, intensive inputs may be economically justifiable if long-term effects on populations are evaluated. If treatments result in a net reduction of the seed bank then the costs can be apportioned to future years and discounted over time since carryover benefits accrue from the treatment. Examples of studies where seed bank decay has exceeded replenishment include Edwards (1980) and Schweizer and Zimdahl (1984a,b).

One way of assessing such changes in populations is by using diagrammatic models (Sagar and Mortimer, 1976). More recently the approach has been to mathematically describe population changes (Mortimer and Firbank, 1983) and use these to simulate the effects of different management regimes (Mortimer, 1983). Two examples in the United Kingdom, where population changes and crop-yield loss have been simultaneously modelled to compare the long-term economic effects of control programmes, involved the annual grasses *A. fatua* and *A. myosuroides* (Doyle *et al.*, 1985; Cousens, 1986). Both studies indicated that in the long term it was economic to treat densities of the weed well below the economic threshold applicable to a single year. For example, with *A. myosuroides* a threshold of 30 plants m^{-2} applied if only the current crop was considered, but over a 10-year run the highest economic returns were attained by treating whenever the population exceeded 7.5 plants m^{-2} . In the case of *A. fatua* the critical density fell from 8-12 plants m^{-2} applicable in a single year to 2-3 plants m^{-2} in the long-term assessment.

A tentative conclusion from these studies points to the regular use of herbicides, which reduce plant populations, being more effective than cultural methods, which destroy seeds once they

have been produced. Although these simulations were found to be insensitive to changes in yield (assumed to be 6.5 t ha^{-1}) and grain price ($\text{£}125 \text{ t}^{-1}$) these are both far higher than those pertaining to Australia so the wider relevance of these conclusions is questionable.

Provided the profitability of cropping is high, producers can afford intensive inputs to control weeds and thus may be less concerned with their efficient use. As profit margins diminish, efficiency becomes more important. In order to reduce the proportion of overall production costs attributable to weed control or to achieve a given level of control for less cost, improved and/or more efficient combinations of weed management strategies will be required - therein lies the value of quantifying population dynamics and using the simulation approach.

CONCLUSIONS

Weed management in crop production involves decision making before carrying out almost every operation because of the complex interactions between weeds and crops during each phase of production (Figure 9.7). Weeds can be so dominant that they completely dictate what cropping enterprise can be pursued and what system of production can be used. Many operations involving weed management need precise timing to achieve optimal results. Weeds therefore place further stringent requirements on the manager for timeliness. Furthermore, weeds damage crop yields and in extreme cases are capable of totally destroying a crop and so place at risk the funds invested in producing crops. Because of these requirements, which need integrated actions, poor weed management decisions can be costly. Furthermore, as production systems become more and more sophisticated, better information is needed for decision making. It is of considerable concern that there are few guidelines available to help producers with these complex decisions. The main resources used appear to be district experience, which is rarely quantified, and farmer judgement.

Since the late 1940s, weed control practices in crops have placed less emphasis on cultural control methods in favour of a heavier reliance on organic herbicides. In Australia this trend has brought about continual expansion of the weed flora, which in turn requires this broader range of species to be treated simultaneously. Presumably this has resulted in an increased proportion of production costs being expended on the treatment of weeds, and has certainly increased the difficulty of containing weed populations. Moreover, the manifestation of a more diverse arable flora is evidence that weed management practices in Australia are not being directed at long-term solutions or goals.

If weed management strategies are to be enhanced or made more efficient, much greater emphasis should be placed on developing integrated systems for regulating populations of mixed species, especially their seed bank components. Ideally these should aim to produce negative population growth rates. It would appear that the best long-term prospects for weed management along these lines lies in developing techniques that directly regulate seed banks. But this possibility is still in the future due to the inadequate understanding of the biological features of weeds that allow them to persist in cropping ecosystems. Furthermore, satisfactory techniques, particularly for understanding in detail the behaviour of seed banks, and those to directly attack seed banks, have yet to be developed. These are major challenges confronting weed science since it would appear that some traditional options for managing weeds are not adaptable to conservation farming techniques, e.g. less opportunity to stimulate weed emergence using cultivation, the inability to use incorporated pre-emergence herbicides in some systems, and poorer interspecific

competition from direct drilled crops. In addition there is some indication that containment of weed populations will be more difficult and will require greater inputs because of a heavier reliance on in-crop control with conservation farming. This will occur, it is suggested, by an upsurge of species with prolonged patterns of emergence. A further danger of relying heavily on chemicals for in-crop weed control is the risk of enhancing the incidence of herbicide resistance.

The dynamics and growth rates of populations underpin decision making and reflect the outcome of weed management strategies. Assessment of the amount of population regulation attained from given inputs of control is now possible by using mathematical models and these open the way for a more analytical approach to weed management. Moreover, they offer the advantage of being able to evaluate alternative options to determine the most economic strategy. It seems entirely logical to strive for such a level of refinement, but continued investment into basic research on weed biology will be required to achieve this.

ACKNOWLEDGEMENTS

Discussions over several years with my colleagues Drs B.A. Auld and D.R. Kemp of this Centre have contributed immeasurably to many of the ideas expressed in this chapter and I further acknowledge their helpful suggestions and critical reading of the manuscript. Appreciation is extended to the Churchill Trust for the opportunity to visit a number of overseas laboratories on a Fellowship as this enabled me to reinforce and refine many ideas, particularly those relating to seed banks. I am grateful to Mr R.D. Murison for fitting the response surface to data presented in Figure 9.6 and to Dr Kemp who helped to organise the structure of Figure 9.7.

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