Competition between crops and weeds in southern Australia

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Introduction

Weeds have co-evolved with crops, and farmers have been trying to develop satisfactory methods for their control since the start of commercial agriculture. The discovery of selective herbicides was a major breakthrough in weed management in field crops, and the use of this group of chemicals has increased consistently over the last 40 years. A wide range of efficient selective herbicides is now available and farmers have adopted them as an important part of weed management. They are continuing to play an important role in reducing cultivation in response to changing economic conditions and the need for soil conservation (Poole 1983). Herbicides are a costly input but, if used correctly, they can result in considerable increases in net returns to farmers. An important part of any economic analysis of a field situation is the accurate prediction of yield loss due to weeds. To date, this area of research has received little attention in Australia. Wells (1978) reviewed the literature on the economics of weed control in broadacre crops in Australia and highlighted the paucity of information on the relationships between weed density and grain yield of different field crops.

The review presented here is limited to Australian studies of competition in the field, and it concentrates mainly on weeds of wheat. However, a few references that are available on other crop species will be discussed briefly. For convenience, the review has been divided into two main sections covering grass weeds and broad-leaved weeds.

Analysis of crop–weed competition

Two approaches are commonly adopted to analyse competition between crops and weeds: replacement series experiments and additive experiments.

(a) Replacement series experiments

In a replacement series experiment the total number of plants per unit area remains the same but the proportion of the two species is varied. De Wit (1960) developed mathematical procedures for describing the course of interference between two species in a replacement series. The substitutive experiments provide a valuable theoretical basis for understanding competition between two plant species but, because of the artificial nature of the approach, its value for describing interference of weeds with crops under field conditions is questionable (Newman 1982) so it will not be discussed in detail in this review.

(b) Additive experiments

In additive experiments two species are grown together and the density of one, usually the crop, remains constant while the density of the other, the weed, is varied. Most experiments on the interaction of crops and weeds employ an additive design. This approach mimics the situation on the farm, where an increase in weed density results in an increase in total number of plants per unit area. The experiments discussed in this review are based on additive designs.

Analysis of experimental data

Several approaches are used to analyse the effects of weeds on crops.

(a) Analysis of variance

Analysis of data by this approach often leads to simple conclusions concerning the weed density required to cause a significant reduction in crop yield. It does not provide any information on the shape of the relationship between weed density and loss in yield. Furthermore, the results obtained are site and season specific and the approach is not flexible enough to develop any general relationships that could be used to predict yield loss. In large field plots it is very difficult to obtain similar densities in different replicates of the same treatment, particularly where natural rather than planted weed populations are used. Analysis of variance of such data often results in apportionment of a large proportion of the total sum of squares into the experimental error component and thus masks small losses in yield at low weed densities. The erroneous conclusion that weeds did not affect crop yield must often be reached under these circumstances.

(b) Generalized models

Square-root transformation of weed density allows the use of linear regression to describe the relationship between weed density and yield loss (Dew 1972). However, the model approaches an infinite slope at low density and an infinite upper limit to yield loss at high weed density (Cousens 1985). It is, therefore, unsuitable for making predictions of yield loss, except perhaps over some poorly defined intermediate density range (Cousens 1985).

Different curvilinear models used in the past for describing competition between crops and weeds, have been reviewed recently by Cousens (1985). Of the 14 models examined, he found rectangular hyperbolae to explain the greatest proportion of variation in the data. However, Gill, Poole and Holmes (1986) used a constrained (X, $Y=0$, 0) exponential model to describe yield loss from competition with brome grass, and found it to be as good as Cousens' rectangular hyperbolae.

Halse (1986) proposed a generalized inverse polynomial relationship that takes into account both crop and weed density to predict yield of a weed infested crop.

$$Y = (fTD) \times Ywo \left(\frac{D\ crop}{D\ crop + D\ weed_1 \times CI_1 + D\ weed_2 \times CI_2 - D\ weed_i \times CI_i} \right)$$

Where Y = predicted yield

(fTD) = a function of total plant density which normally equals 1

Ywo = weed-free yield

$D\ crop$ = density of crop plants

$D\ weed_{(1-i)}$ = density of weed plants

$CI_{(1-i)}$ = competition index; a parameter which determines the slope of the curve, and equals the inverse of the number of weed plants which equal one crop plant in competition.

This model produces curves similar in shape to the exponential model and the rectangular hyperbolae. However, it addresses the problem of infestation with more than one weed in crops of different potential yield and takes account of crop density and the inherently different competitive effects of weeds. Weed scientists could explore further the value of this model.

All of these models describe grain yield as a function of weed density and not weed biomass. From a physiological viewpoint, biomass is the key factor that determines uptake of nutrients and water and interception of radiation by a plant species. There is generally a linear relationship between weed biomass and loss in crop biomass, which translates to crop grain yield if there is adequate moisture available during grain-filling (Hawton 1980). However, weed biomass (which is commonly measured at crop anthesis) is of no use for predicting loss in yield due to weeds at the early seedling growth stage as it is too soon for the yield potential of the crop to have been seriously affected. Therefore, we feel that the use of weed density in crop–weed competition models intended to be used for prediction of loss in yield is justified, despite several shortcomings which are discussed later; weed scientists should persist with this approach.

Effects of grass weeds on crop yield

Grass weeds are generally more troublesome than broad-leaved weeds in cereal crops, and herbicides used to control grasses are often expensive. Poole (1986) estimated that in 1985, in Western Australia, about $40 million was spent on grass control and $10 million on broad-leaved weed control.

Wild oats

Wild oats (*Avena fatua* L. and *A. ludoviciana* Durieu) are common weeds throughout temperate Australia (Burbidge and Gray 1970). The predominance and persistence of wild oats in cereal crops are considered to be due largely to their well-developed seed dormancy (Paterson *et al.* 1976). In Western Australia, the importance of wild oats as a weed of wheat crops of different yield potentials was highlighted by Paterson (1969). McNamara (1972) reported that in Queensland a crop with yield potential of 2.7 t ha^{-1}, as few as 3 plants m^{-2} of wild oats could reduce the grain yield by 68 kg ha^{-1}. There are no data presented in this paper, but we assume that such a figure was obtained by the extrapolation of the linear regression of grain yield on weed densities, as reductions in yield at such low weed densities in the field are likely to be masked by large variability in the data. In northwestern New South Wales, Philpotts (1975) using low seeding rates of wheat (28–32 kg ha^{-1}), found that a wild oat density of 27 plants m^{-2} reduced the grain yield of wheat by 50%. At its face value, seeding rate of 28–32 kg ha^{-1} seems adequate, however, assuming an average grain weight of 35 mg per seed, the crop density achieved by Philpotts (1975) was approximately 40% lower than would generally be expected at those seeding rates.

In five trials carried out on the Darling Downs, Queensland, Wilson (1979*a*) found that *Avena* spp. caused yield reductions (best herbicide treatment versus untreated) of 15% to 56%. Reeves *et al.* (1973) found yield reduction of nil to 46% in 21 trials conducted in Victoria. A common feature of the two studies discussed above was that a significant proportion of wild oat plants escaped the control measures and this could have resulted in underestimation of yield losses. Based on these data, Wilson (1979*b*) estimated a possible $43 to $62 per hectare increase in gross margin due to an effective control of wild oats under a high yielding situation (2.5 t ha^{-1}).

McNamara (1976) studied the effects of time of removal and found that wheat crops from which wild oats were removed as early as 25–30 days after

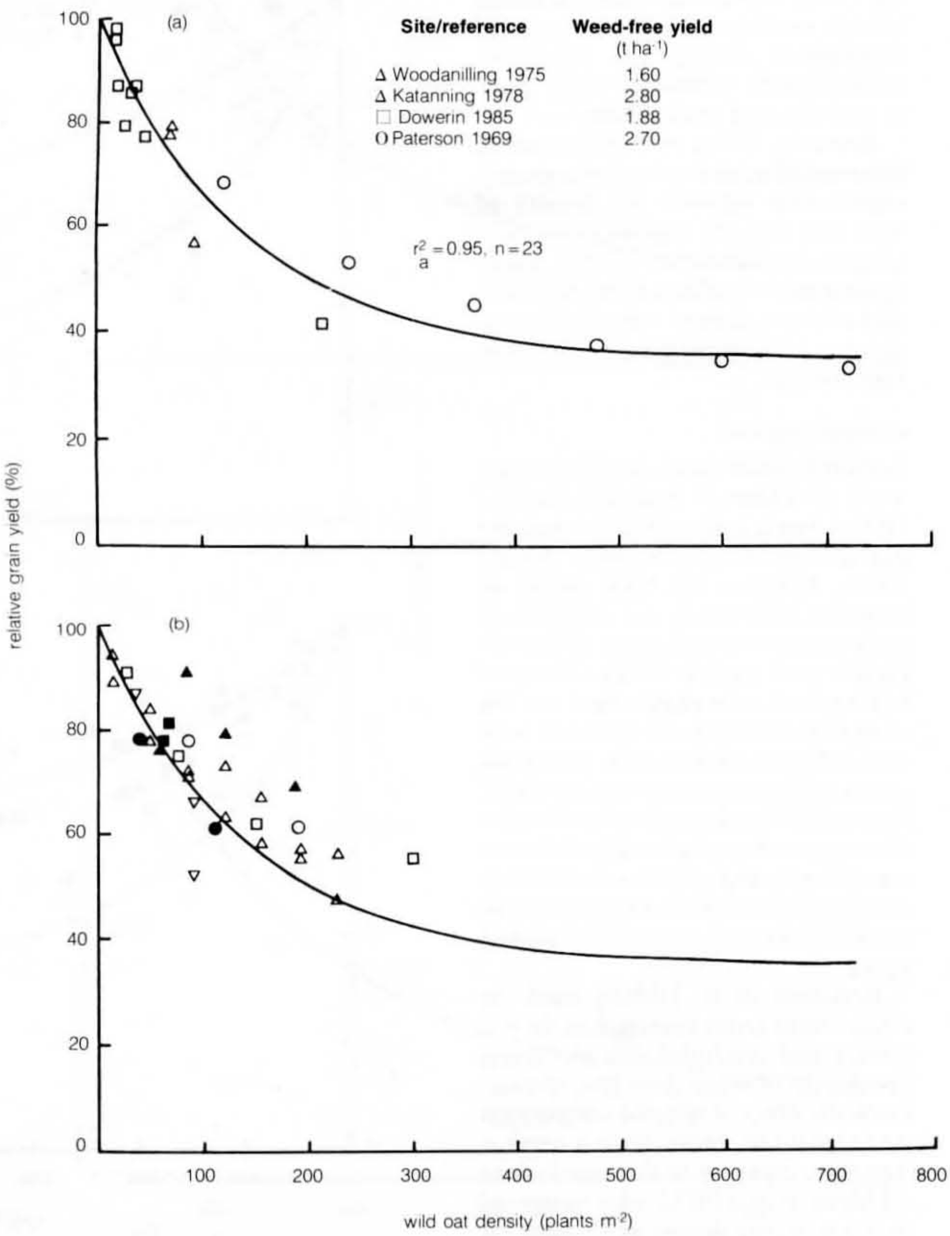

Figure 1 The relationship between the density of wild oats and the relative grain yield (expressed as a percentage of the weed-free yield): (a) the fitted curve and (b) comparison of the fitted curve with the data from Bowden and Friesen 1967 (Δ), Bell and Nalewaja 1968 (O), McNamara 1976 (●), Anderson 1978 (∇), Wilson 1979 (■), Radford *et al.* 1980 (▲), and Anon. 1982 (□).

sowing did not recover completely from competition and did not achieve the yields obtained in weed-free plots. Furthermore, he found that the loss in yield increased with increasing duration of competition, although some benefits could still be expected from weed control as late as 75–100 days after sowing.

On black earth soils, with large amounts of stored water, the rate of seeding wheat influenced its competitive ability against wild oats (Radford *et al.* 1980). They found that the lowest seeding rate required to produce 'optimum' grain yield at a site was higher in wild oat infested plots than in weed-free plots. Unfortunately, high seeding rates deplete soil moisture reserves more rapidly than low rates and this can lower the yields when soil moisture is limiting (Fawcett 1964; Pelton 1969). Therefore, beneficial effects of high seeding rate of wheat on weed suppression during the vegetative growth can be nullified by water stress at anthesis and grain-filling.

Recently, Gill *et al.* (1986) used an exponential model to develop a general relationship between the density of wild oats and the relative grain yield (Figure 1). Validation of this model against published data from Australia and overseas showed remarkable consistency in the weed density–yield loss relationship.

Annual ryegrass

Lolium rigidum Gaud. is an important weed of wheat in Australia (Reeves 1976*a*), but it is also a highly regarded pasture species (Cariss 1962; Donald 1970). Ryegrass has been shown to compete with wheat for nitrogen as early as the two-leaf stage of growth (Smith and Levick 1974). Time of sowing had a marked effect on the competitive ability of ryegrass with wheat (Reeves 1976*a*), with later sown crops suffering greater loss in yield. Reeves (1976*a*) also pointed to the consistency in the relationship between weed density and yield loss in his trials and suggested that it was possible to predict yield loss in ryegrass infested crops.

Rerkasem *et al.* (1980*a*) used the replacement series approach of de Wit (1960), and concluded that increasing the density of wheat does little to overcome the effect of ryegrass competition on the yield of wheat. Such a result is however, contrary to the conclusions of Medd *et al.* (1985), who suggested increase in crop density as a means for reducing competitive effects of annual ryegrass. Such a difference in the conclusions from the two studies could be a reflection on the artificiality of the substitutive approach used by Rerkasem *et al.* (1980*a*). Altering the spatial arrangement of the crop did not affect the relationship between wheat yields and ryegrass density during a 3-year study in central western New South Wales (Medd *et al.* 1985).

Time of emergence and establishment of ryegrass relative to the crop is also likely to be important in determining the outcome of competition between the two species. Rerkasem *et al.* (1980*b*) found competitive ability of ryegrass to be low when it germinates after wheat.

In a preliminary investigation, Reeves (1976*b*) found that four different genotypes of wheat did not differ in their competitive ability against ryegrass. Subsequently, however, Reeves and Brooke (1977) reported differences between wheat varieties in their ability to compete with ryegrass, but they could not correlate this with differences in height, tillering or dry matter accumulation between the varieties. Later, LeMerle, Michael and Sutton (1979) showed triticale (*Triticum* × *Secale*) to be less sensitive than wheat to competition from ryegrass. Poole (1979) compared barley and

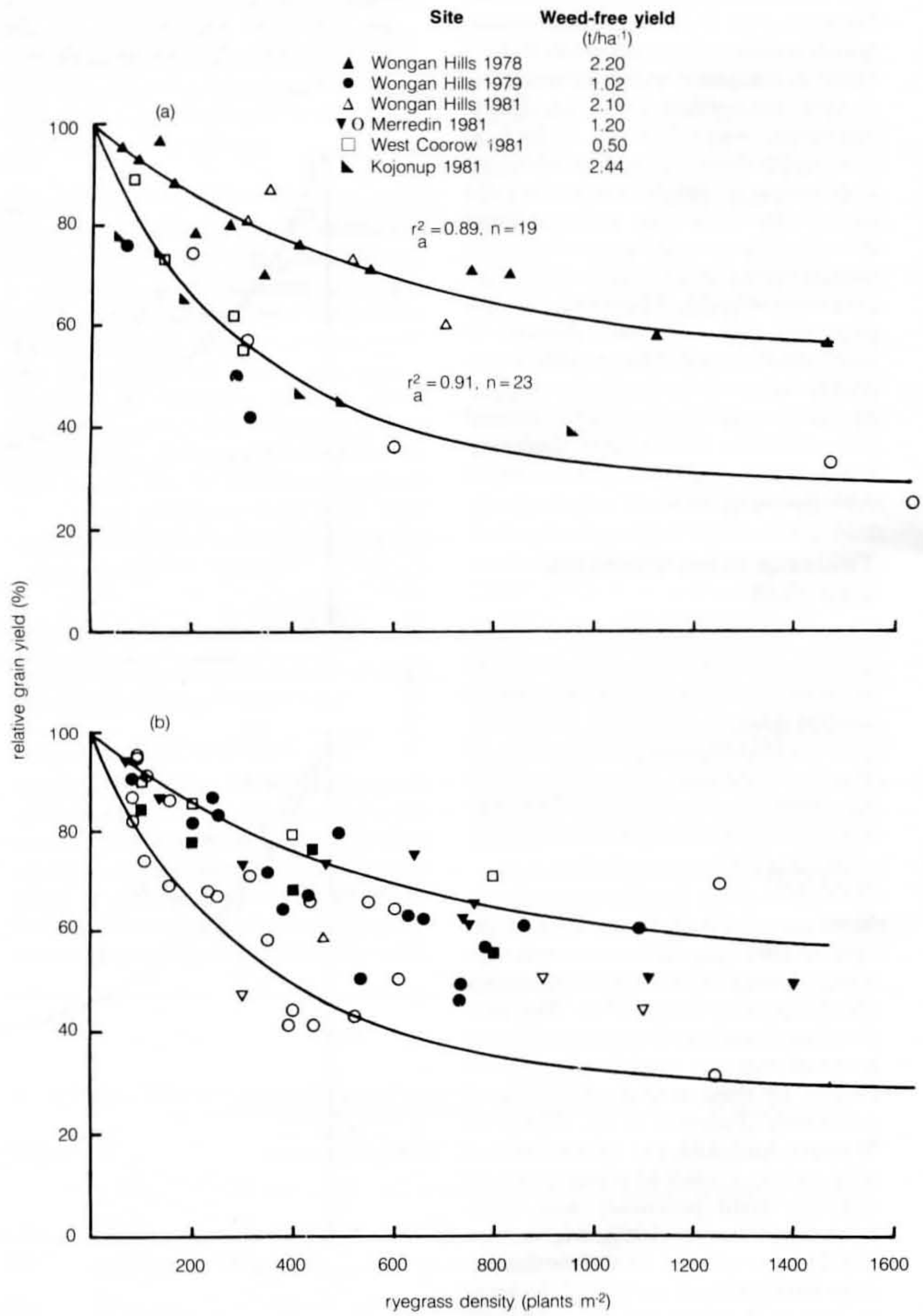

Figure 2 The relationship between the density of annual ryegrass and the relative grain yield of wheat (see caption to Figure 1): (a) the fitted curves and (b) comparison of the fitted curves with the data from Smith and Levick 1974 (Δ), Reeves 1976 (□, ■), Anderson 1978 (▽), unpublished data of Moore (▼, ●), and 16 diclofop-methyl trials of W.A.D.A. (○).

wheat for competitiveness with ryegrass and found that barley was less affected than wheat at equivalent densities of ryegrass. More vigorous tillering and prostrate growth habit of barley may explain this difference.

Our results from trials on competition between wheat and annual ryegrass, showed to distinct relationships (Figure 2). The ability of ryegrass to compete with wheat was correlated with the rainfall during the early germination and seedling establishment phase (Gill and Poole 1986). Such climatic factors are likely to be more important for the establishment of weeds with small seeds because they generally have slower rates of radicle extension (Baker 1972). Further work needs to be done to demonstrate clearly the importance of different climatic factors at the break of the season in determining ability of ryegrass to compete with wheat.

Narrow leafed lupins (*Lupinus angustifolius*) are also affected by competition from ryegrass. Allen (1977) found that when ryegrass at 10 plants m^{-2} germinated six weeks before lupins, grain yields were reduced by 70%. When 90 plants m^{-2} of ryegrass germinated with the crop, the yield fell by 47%, but the same density of ryegrass germinating six weeks after the crop did not affect lupin yield. Lupins sown at 11.2 plants per metre of row were slightly more competitive than lupins established at 5.6 plants per metre of row. Arnold *et al.* (1985) found that 40 ryegrass plants m^{-2} reduced Uniharvest and Unicrop lupin yields by 34%.

Brome grass

Brome grass (*Bromus diandrus* Roth), also known as great brome, is native to the Mediterranean region and after its introduction to Australia it spread through the temperate agricultural areas of southern Australia (Burbidge and Gray 1970). Despite ecological studies which suggest brome grass should be easy to control in cropping programmes because of its lack of dormancy and evenness of germination, it has risen in stature as a weed over the last few years (Gill and Blacklow 1985; Harradine 1986). This appears to be due to the introduction of reduced tillage techniques of crop establishment, to reduced competition from other grass weeds (e.g. ryegrass and wild oats) and broadleaf weeds which can now be effectively controlled with selective herbicides, and in some areas to a decline in the numbers of sheep grazing brome grass infested pastures (Gill, Poole and Holmes 1987).

Brome grass has been shown to compete successfully with wheat for soil nitrogen which results in large losses in grain yield (Gill and Blacklow 1984; Gill 1985). Recently, Gill *et al.* (1987) analysed the results of six field trials in Western Australia and concluded that yield losses due to competition from brome grass were consistent over seasons and sites and, therefore, it was possible to develop models for predicting yield loss in wheat due to competition (Figure 3).

Barley grass

Barley grass (*Hordeum leporinum* Link) was introduced to Australia soon after settlement (Kloot 1981) and now

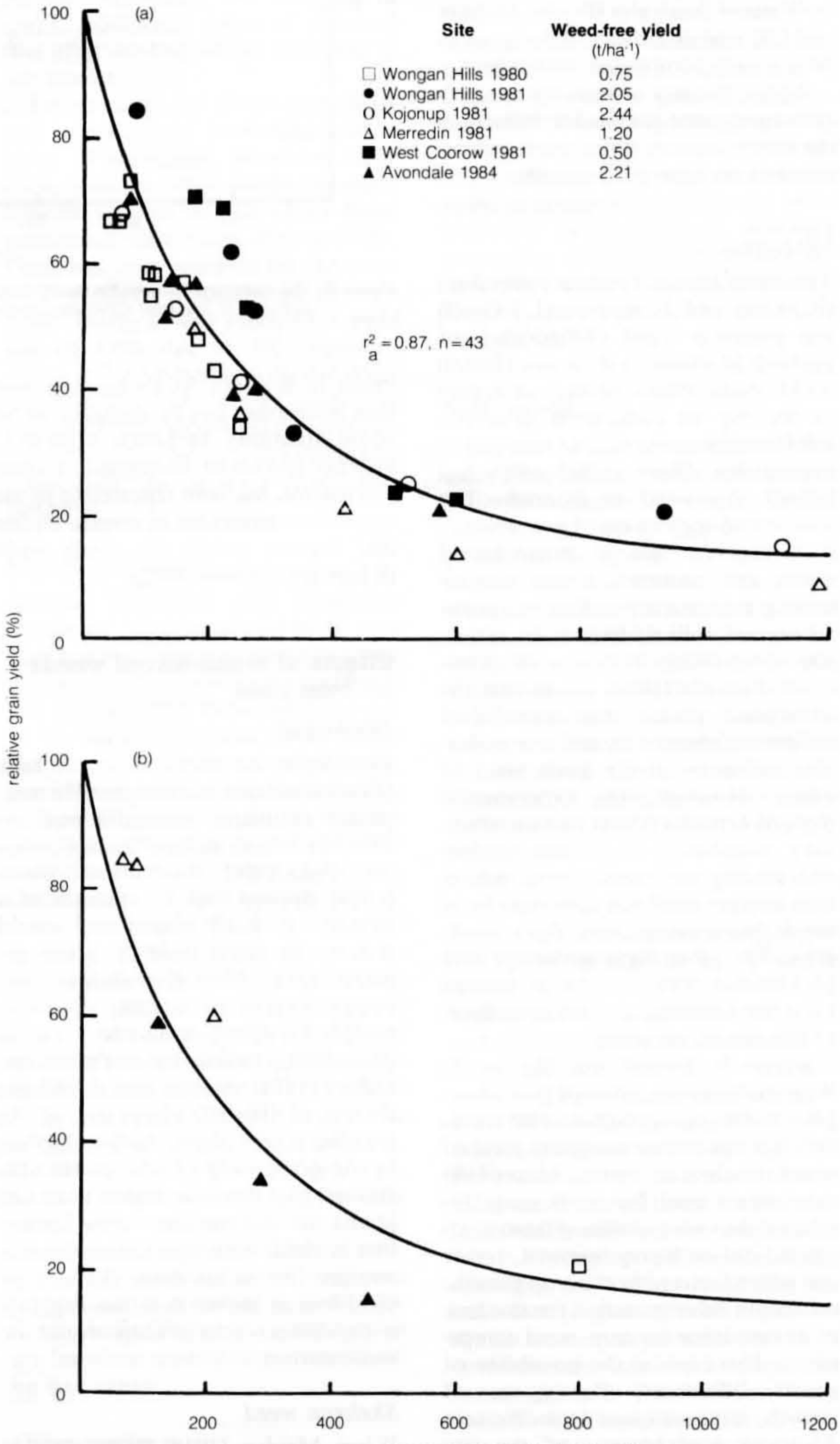

Figure 3 The relationship between the density of brome grass and the relative grain yield of wheat (see caption to Figure 1): (a) the fitted curve and (b) comparison of our fitted curve with the data from Gill and Blacklow 1984 (□), and our experiments at Geraldton (Δ) and Avondale (▲) during the 1985 season.

the species is widespread in Australia (Cocks *et al.* 1976). Recently, Kloot (1981) reassessed the ecology of barley grass in Australia and concluded that increase in soil compaction, for example, by minimum tillage, and rise in soil pH favoured invasion of pastures and crops by barley grass. There is little quantitative information on loss in wheat yield due to infestation by barley grass. Trials carried out in Western Australia (Poole, Holmes and Gill 1986*a*) showed barley grass to be a strong competitor with wheat.

Again, the lack of suitably selective post-emergence herbicides influences the importance of barley grass competition as an area for research.

Silvergrass

The silvergrasses (*Vulpia bromoides* (L.) Gray and *V. myuros* (L.) Gmel) are common weed components of pastures in southern Australia (Dillon and Forcella 1984). Silvergrass is very susceptible to cultivation (Forcella 1984), and it seems that an increase in area under direct drilled crops has helped this weed to flourish. The widespread application of new selective herbicides for use in broad-leaved crops and pastures, which control other grasses but are ineffective against silvergrass, is likely to alter the botanical composition in favour of silvergrass. Forcella (1984) found that the silvergrass plants that established before mid-August caused a considerable reduction in the grain yield of wheat. However, the experimental plots of Forcella (1984) had an 'abundant' population of *Lolium rigidum* and *Rumex acetosella*, both species with a larger plant size and likely to be much more competitive than silvergrass. Therefore, we consider the data of Forcella (1984) to be of limited value for assessing competitive effects of silvergrass on wheat.

Research carried out by us in Western Australia, showed that silvergrass at densities as high as 3000 plants m^{-2}, did not reduce the grain yield of wheat (Poole *et al.* 1986*b*). Most of the data points used for developing this relationship were obtained from trials carried out on heavy textured, fertile soil which fostered heavy crop growth; this could be responsible for the lack of any evidence for crop–weed competition. There is also the possibility of genetic differences, affecting rate of growth, in populations from Western Australia used by us and the one investigated in the ACT by Forcella (1984). Anecdotal evidence from Victoria and South Australia, and light crops in Western Australia, suggests that silvergrass can be competitive in some situations. In South Australia, another species of silvergrass, *Vulpia fasciculata*, has been reported to be an aggressive competitor of cereals, lupins and lucerne grown on sandy soils (Kloot and Symon 1982).

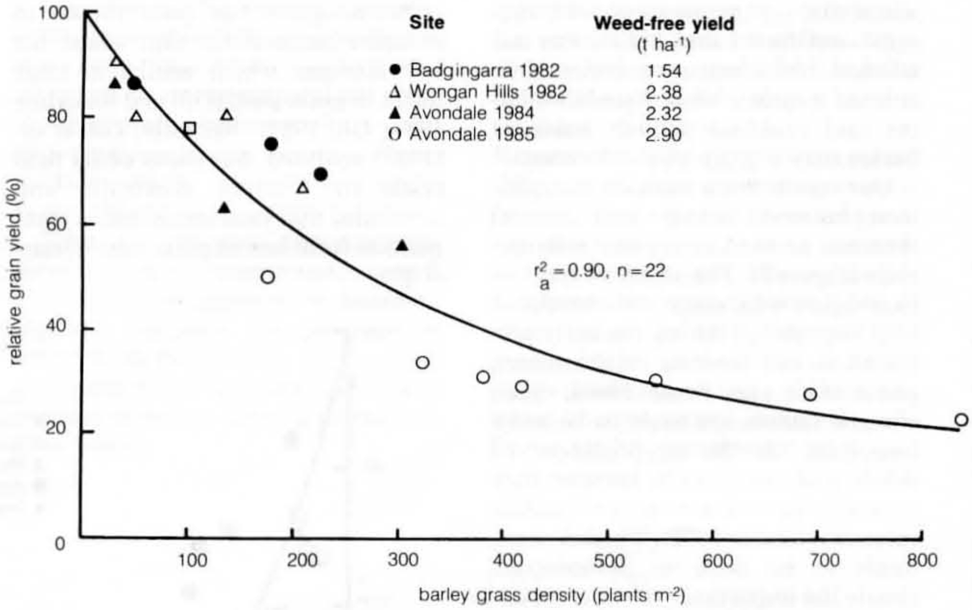

Figure 4 The relationship between the density of barley grass and the relative grain yield of wheat (see caption to Figure 1). The fitted curve was compared with the results of Thorn and Perry 1983 (□).

Effects of broad-leaved weeds on crop yield

Doublegee

Doublegee or three-cornered Jack (*Emex australis*) is widespread in temperate mainland Australia and on Flinders Island in Bass Strait (Gilbey and Weiss 1980). Hawkins and Black (1958) showed that *E. australis* at a density of 8–12 plants m^{-2} could reduce the grain yield of wheat by about 40%. They also showed that competition in the seedling stage was mainly for nitrogen and later on, at grain-filling, mainly for soil moisture. Gilbey (1974) showed that doublegee density of 100–120 plants m^{-2}, at the seedling stage, caused 50% reduction in the grain yield of wheat. He also showed that densities higher than 120 plants m^{-2} did not cause any further loss in yield. Although Gilbey fitted a straight line to his data, the lack of yield loss at higher densities suggests a curvilinear relationship would be more correct.

Skeleton weed

When Maiden (1918) first recorded skeleton weed (*Chondrilla juncea*) in Australia, he wrote 'It is going to be one of the most troublesome weeds heard of for some time'. Skeleton weed is now recognised as being the most serious weed of south-eastern wheat growing regions of Australia (Cuthbertson 1967; Groves and Cullen 1981).

Myers and Lipsett (1958) found nitrogen to be the major factor limiting yields of wheat and oats infested with skeleton weed and competition affected early crop growth. They also found that high nitrogen levels in the soil, achieved either by fertilizer application or when the crop followed a legume-rich pasture, reduced the competitive effects of skeleton weed on cereal grain yield.

Cuthbertson (1969) found an exponential relationship between the ground cover of skeleton weed and relative yield (yield following preplanting weed control expressed as a percentage of the yield following commercial weed control) of wheat. He also suggested that about 20% ground cover of skeleton weed would warrant adoption of control measures, however, the economic feasibility of such control measures would be determined by the absolute rather than the relative response.

Skeleton weed has also been shown to be a strong competitor for soil moisture during the reproductive phase of the cereal crops. Data in Table 1 from Cullen (1978), based on the data of Wells (1970) demonstrate the effect of competition for soil moisture.

Cruciferous weeds

Wild radish (*Raphanus raphanistrum*) is a common weed of cereal and grain legume crops in southern Australia

Table 1 Average wheat yields at different densities of skeleton weed (excess nitrogen supplied but soil moisture limiting). After Cullen (1978) and Groves and Cullen (1981), based on data of Wells (1970)

Density of *C. juncea* (rosettes m^{-2} in crop)	**Yield** (t ha^{-1})
1–10	1.38
11–100	0.75
>100	0.31

(Piggin *et al.* 1978). Little research has been reported on yield losses caused by wild radish populations. This is surprising as millions of hectares of cereal crops have been sprayed annually with phenoxy herbicides since the 1950s when these compounds were developed. Several studies on the ecology of radish have been carried out, but this work has ignored effects on crop yields (Reeves *et al.* 1981; Cheam 1986). With wild radish, interest in control goes beyond yield loss, as the weed causes harvesting and grain contamination problems and often these are primary reasons for control (Reeves *et al.* 1981).

The only attempt to derive a general relationship for the effect of wild radish on wheat yield is that of Moore (1979) who found, at three widely different sites in Western Australia, that 25 plants m^{-2} of radish emerging with the crop gave 7–11% yield reduction, 50 plants 15–20% reduction, 75 plants 19–26% reduction and 100 plants m^{-2} 25–33% reduction. At Rutherglen, Victoria, Code *et al.* (1978) reported yield reductions of 11, 26, 35 and 49% for radish densities of 10, 50, 100 and 200 plants m^{-2} respectively, while Code and Reeves (1981) reported 10% yield loss of wheat with a radish density of only 7 plants m^{-2}. Often radish plants continue to emerge for several weeks after crop emergence (Cheam 1986; Reeves *et al.* 1981). Moore (1979) found that up to 50 radish plants sown 4 weeks after crop establishment caused no yield reduction.

Yield reductions of this order rank wild radish with wild oats as one of the more damaging weeds of cereal crops.

Other cruciferous weeds, such as wild turnip (*Brassica tournefortii*), wild mustard (*Sisymbrium orientale*), and rapistrum (*Rapistrum rugosum*), are often significant weeds of cereal crops, however, we could find no published data on their competitive effects in crops. Their growth habit is similar to wild radish and it is likely they offer similar competitiveness.

Capeweed

Capeweed (*Arctotheca calendula*) is able to survive moisture stress at the beginning of the growing season (Rossiter 1966). Frequently, this characteristic allows capeweed seedlings to survive cultivation and establish in crops. Additional waves of germination after seeding of the crop add to the weed burden.

Young capeweed plants are readily and inexpensively controlled with a range of herbicides. However, large transplants or older weeds are more difficult to control and often cause substantial yield losses (Peirce 1986). Little has been reported on the competitive effects of capeweed on crop yield. Peirce (1986) reported a yield loss of 25% due to 300 capeweed plants m^{-2} establishing with the crop. He suggests that large losses are sustained when capeweed survives cultivation and a relatively low density of transplants can severely affect crop yields.

Clovers and medics

Annual *Trifolium* and *Medicago* species are intentionally added to crop stands when they are undersown as a pasture establishment technique (Poole and Gartrell 1970; Brownlee and Scott 1974), but subterranean clover is also frequently present as a weed in crops, particularly in crops established using reduced tillage techniques. In Western Australia, Poole and Gartrell (1970) found that establishing subterranean clover under a crop at seeding rates of 4 and 10 kg ha^{-1} reduced wheat yield by about 20%. The clover densities attained were not recorded but, in another experiment (M. L. Poole unpublished data), Nungarin subclover at 100 plants m^{-2} reduced wheat yield by 10% when nitrogen was not added to the mixture but, when nitrogen was added, wheat yield was unaffected. However, at 350 clover plants m^{-2}, yield of wheat was reduced by 27% even when nitrogen was added. Brownlee and Scott (1974) found similar yield losses when barrel medic was undersown in crops in western New South Wales. The results quoted above are for wheat seeding rates in the 40–60 kg ha^{-1} range.

Other species

We were not able to find published information on yield losses caused by some common weed species in crops such as soursob (*Oxalis pes-caprae*), dock (*Rumex* spp.) and sorrel (*Rumex acetosella*). Reeves (1970), gives some data on toad rush (*Juncus bufonius*) and loosestrife (*Lythrum* spp.) which he suggests become serious competitors with wheat under wet conditions. Pratley (1983), working with mixed populations of *Amsinckia hispida* and toad rush in wheat, found that control of densities of 721 m^{-2} and 767 m^{-2}, respectively, of these species with terbutryne improved yields by 1.22 t ha^{-1} under good growing conditions and by 0.42 t ha^{-1} under poor conditions. Wells (1979) compared the competitive effects of several lesser weeds of cereals and found that on a per plant basis the order of competitive ability was white ironweed (*Lithospermum arvense*), amsinckia, wild turnip (*Brassica tournefortii*), deadnettle (*Lamium amplexicaule*) and fumitory (*Fumaria parviflora*).

Discussion

It has been said that man spends more time controlling weeds than on any other occupation. However, despite this constant surveillance of his weed problems, he appears to have made surprisingly few attempts to predict with any accuracy the extent of yield losses which might occur. The myriad conditions under which crops and weeds cohabit in the field make this a challenging task and the question remains whether it is indeed possible to develop weed density–crop loss relationships for anything beyond tightly defined agronomic and environmental conditions.

For this review we brought together work on crop–weed competition as it applies to cereal crops in the temperate cropping regions of Australia. Despite the diversity of the information available, we conclude that for some important weeds it is possible to derive relationships which are useful when making weed management decisions under wide-ranging conditions, extending at least to the regional level. For example, our data for brome grass in wheat (Figure 3) which are drawn from widely different sites and seasons within a broad agricultural region (the wheatbelt of Western Australia) and wild oats (Figure 1) where data are drawn from a much wider sample of environments are both cause for encouragement. On the other hand, the data for annual ryegrass in wheat (Figure 2) suggest that some understanding of the effects of environmental conditions encountered during crop establishment will be necessary before density can be used for crop loss prediction. However, in the last case, as an interim measure until more definitive data can be assembled, it may be possible to describe either two or more curves which take account of establishment conditions or an area between boundary curves which allow some assessment of likely yield losses (Figure 2).

We conclude that further effort is justified to derive general relationships for specific crops and weeds on a regional basis.

Interest in weed density–crop loss relationships by farmers and their advisers is likely to be limited to lower weed densities. For example, farmers have little difficulty in deciding that it is profitable to control wild oat infestations of 200 plants m^{-2} in well grown crops and will not require 'crop loss' models to help them. Interest will be focused on the weed density range of 0–150 plants m^{-2} for most weed species in Australian cereal crops. From the information we have gathered, the yield loss associated with several important weeds at 100 plants m^{-2} in cereal crops sown at normal densities (80–150 plants m^{-2}) is presented in Table 2.

It is in the 0–150 plants m^{-2} range that increase in yield loss with increasing weed density is greatest and nearly linear. For example, in the case of brome grass (Figure 3), yield loss from the first 50 plants is 17%, for the next 50 a further 13%, while for the 50 plants from 400–450 reduction in yield loss is only a further 7%.

The concept of a 'critical weed density' where it will pay to intervene with a control measure is often raised (Wells 1978; Glauninger and Holzner 1982). We suggest that this only has meaning for very tightly defined conditions of crop and weed growth and is of little use as a predictive tool. Using brome grass competition (Figure 3) as an example, it is obvious that absolute yield loss, which interests farmers most, for a particular weed density will depend upon crop size (yield). Here yield loss from 100 brome grass m^{-2} for crops yielding 750, 1500 and 3000 kg ha^{-1} will be 225, 450, and 900 kg ha^{-1} respectively. This implies that the 'critical weed density' would vary with changing absolute yield. This is a very important point and is often ignored when weed control advice is given. Poole and Gill (1986) suggest two-way tables (Table 3) as well as describing a simple computer model to handle this.

Burgess and Gill (1986) have taken this a step further with an elegant graphical representation combining crop potential, weed density, crop price, yield loss and income forgone (Figure 5). They have generated similar curves for wild oats, ryegrass and barley grass.

Table 2 Yield loss in wheat in southern Australia due to competition with some important annual weeds (*ca.* 100 plants m^{-2})

Weed	Percentage loss	Source
wild oats	32	Gill *et. al.* (1986*a*)
brome grass	30	Gill *et al.* (1987)
barley grass	24	Poole *et al.* (1986)
ryegrass	8–20	Gill and Poole (1986)
wild radish	25–35	Moore (1979) Code and Reeves (1981)
doublegee	40	Gilbey (1974)
subterranean clover	10	Poole (unpublished)

Table 3 Wheat grain yield loss caused by brome grass at different densities in crops of different weed-free yield potentials

Potential weed-free yield (kg ha^{-1})	Brome grass weed density (plants m^{-2}) 25	50	100	200	300	400
750	67	127	225	367	457	517
1000	90	170	300	490	610	690
1500	135	255	450	735	915	1035
2000	180	340	600	980	1220	1380
3000	270	510	900	1470	1830	2070

An important question facing weed scientists is how far to go, in refining weed density–crop loss relationships. That is, if man's quest for knowledge is put aside for the moment, what precision is required for making decisions in the field? Will the level of precision offered by the brome grass and wild oat relationships (Figures 1 and 3) or even the dual curves of the ryegrass relationship (Figure 2) be adequate for field use? We have considerable confidence that the brome grass relationship will suffice for the broad region of the Western Australian wheatbelt (10 million hectares), pending some further validation at low brome grass densities. For wild oats on the other hand, we suggest that while the curve derived is a good fit (Figure 1) the spread of points at lower densities, and the Australia-wide importance of wild oat in terms of both extent and severity of crop loss, deserves considerably more attention and local modification.

Several interesting practical and theoretical questions remain unanswered.

Agronomic manipulation of weeds

Manipulating crop density (Radford *et al.* 1980; Martin 1986) and nitrogen nutrition (Myers and Lipsett 1958), to improve the competitiveness of the crop at the expense of the weeds, have been suggested as weed control measures. While such interactions have frequently been demonstrated, and are acknowledged in the Halse equation described earlier, they often only assume importance at densities much lower than are commonly used for crop production. These lower densities are often found in de Wit replacement series experiments or at very high crop densities where factors such as lodging, disease and excessive water use may introduce a new set of problems. Doubling normal crop density is generally far less cost effective than equivalent expenditure on selective herbicides. However, gains can be made in some circumstances and Martin (1986) suggests higher crop seeding rates to combat wild oats in northern N.S.W. In Western Australia, the benefits from increased seeding rates in brome grass and ryegrass infested crops have been small (M. L. Poole and J. E. Holmes, unpublished data).

We suggest that nitrogen fertilizer, which is expensive, is unlikely to be added to crops as a primary weed control technique. Direct intervention with herbicides will generally be more profitable. The literature is divided on the merits of addition of nitrogen to crop–weed mixtures. Nalewaja (1964) and Gruenhagen and Nalewaja (1969) found that adding nitrogen favoured the weed, but other workers (Black-

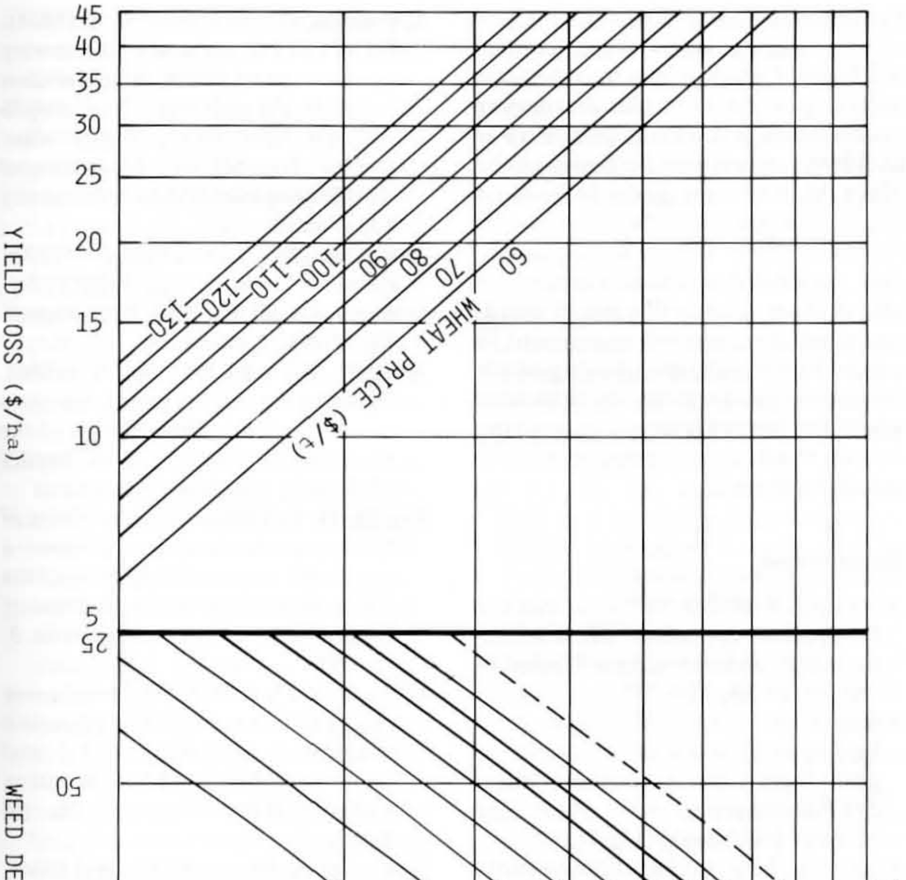

Figure 5 A 'weedcost' ready-reckoner for brome grass in wheat crops in Western Australia showing the relationship between yield loss, weed density, weed-free yield and price of wheat.

man and Templeman 1938; Myers and Lipsett 1958; Hawkins and Black 1958) showed that it favoured the crop. Alkamper (1976) reviewed the literature and concluded that fertilizer application can remedy the early-season crop damage from weeds only in crops where the weed density is low. Furthermore, weed control measures and fertilizers should always be applied jointly. Our results (M. L. Poole unpublished data) with ryegrass and the data of Wells (1979) with some broadleaf weeds suggest that, at normal crop densities and nitrogen nutrition levels, interactions between nitrogen supply and weed competitiveness are slight. It is likely that commercial agronomic practices, such as seeding rate, already reflect some allowance for weeds in crops as they have generally been developed under conditions of moderate weed infestation.

Mixed weed populations in crops

An area of great importance which has been almost ignored in the literature is the very common field problem of the presence of two or more weeds in a crop. The Halse equation, described earlier, raises this issue by assigning competitive indices to each weed but has yet to be tested for its usefulness in handling this. The rectangular hyperbola described by Cousens (1985) could readily accommodate additional terms to modify crop-loss relationships derived from 'single weed species' trials, but Cousens does not raise this issue. The exponential function used by the authors is less flexible than the Halse and Cousens approaches.

Haizel and Harper (1973) used an additive design in a pot study to investigate competition between different components of a three-species mixture of barley (*Hordeum vulgare*), white mustard (*Sinapis alba*) and wild oats (*Avena fatua*); they concluded that the effect of a mixture of weeds on a crop cannot be predicted from the effects of the weed species acting separately. These results also showed that the selective elimination of wild oats from the three-species mixture was an advantage if done at the pre-emergence stage; but post-emergence removal of wild oats, or removal at any time of white mustard from the weed mixture, brought little benefit to the remaining barley. Unfortunately, such studies are rare and the authors could not find any example of field research on competition between a crop and mixture of weeds.

In the Australian context, wild oats and barley grass often occur as mixed populations in wheat crops. Diclofop-methyl is very effective against wild oats but has little effect on barley grass. If wheat is sprayed within a few weeks of emergence with diclofop-methyl, the wild oats will be removed, but the space (*sensu* de Wit 1960), which in a wheat–wild oat mixture would become available only to wheat, in a three-way mixture from which one component is removed would be shared by the remaining two—the wheat and the barley grass. The herbicide may also temporarily slow crop growth making the crop less competitive with the non-susceptible weed. The net returns from the application of diclofop-methyl would be greatly diminished under these circumstances. Examples abound where this is likely to happen, and they range from relatively straightforward mixtures of grass and broad-leaved weed (e.g. wild oats and wild radish) to complex mixtures of several weeds. Even the wild oat-wild radish situation, where both can be readily removed with herbicides, becomes complex when removal must be separated by time because of herbicide compatability constraints and the requirement to apply phenoxy herbicides after flower initiation.

Effectiveness of herbicides

When evaluating yield losses derived from crop-weed competition studies, it is tempting to take the yield difference between the weed-free and the weedy situation as the value which will accrue if a control measure is invoked. This will invariably be an overestimate of the likely gains, particularly in the case of herbicides applied after crop emergence. Apart from the damage to the crop (Elliot *et al.* 1975) and the reduced competitiveness which the herbicide may cause, herbicides applied after crop emergence are seldom applied early enough to prevent completely the weed reducing crop yield (Rerkasem *et al.* 1980*c*); the herbicide may miss some weeds; herbicides are often not fully effective and may either allow some survivors or merely suppress weed growth; and tolerance to herbicides may exist in the weed population (Heap and Knight 1986). Competitive relationships will require adjustment for this in the light of experience and experiment.

Weeds of different ages

Weeds which emerge before the crop are much more competitive than those emerging after the crop (Allen 1977). Most of the weed situations described in this review are for weeds germinating at about the same time as the crop, unless otherwise stated. However, in the field, infestation with weeds which survive seedbed preparation is common (Peirce 1986), as are waves of germination in the crop, with wild radish the most quoted example (Reeves *et al.* 1981; Cheam 1986). Modification of density-yield relationships will be required to allow for these circumstances.

Conclusion

Despite the difficulties raised, we believe that weed density-crop yield loss relationships can be derived, and for broad regions will be valuable aids when deciding upon weed control strategies. Certainly much of the $160 million spent on herbicides in cropping programmes in Australia (Blacklow *et al.* 1984) is spent with little idea of the effect the weeds are likely to have on the crop. Attention in the past has concentrated upon killing weeds, rather than deciding first whether it is worth killing them. Unless this is addressed, vast sums of money will continue to be wasted in Australia on spraying weeds unnecessarily, spraying in situations where the herbicide does not have the desired effect, or not spraying when it would have paid.

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