Theory and reality of weed control thresholds

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Summary

The many ways in which weed control thresholds can be defined are discussed. Attention is drawn to the loose terminology and confusion within the literature. Emphasis is placed on fallacious statistics in the calculation of competition thresholds and the practical irrelevance of the statistical threshold. Economic threshold calculations are presented to show how they vary with herbicide cost, performance and grain price. Other important factors which should be incorporated into thresholds are discussed. A selection of published values for thresholds are given. Problems in population surveys, yet to receive attention, are highlighted. It is emphasized that there have been few attempts to put thresholds into action and that the attention they are currently receiving is unwarranted. Finally, arguments are made that exactness in definition and application are not essential, that subjectivity is an acceptable component in weed management, and that far more important than thresholds is the need for data from which they, and other things, can be calculated.

Introduction

In recent years agricultural overproduction in some countries (Avery, 1986) has resulted, if not in lower prices, in considerably reduced profit margins for certain commodities. The realization that maximization of profit is not synonymous with maximization of yield is leading to a change in emphasis by the agricultural industry. For example, research institutions and advisory services in the U.K. are now being directed towards more efficient production and improvements in crop quality (Bell 1984; Selborne 1985). Farmers are looking more urgently at how they may cut costs in order to achieve maximum profitability, even to the extent of accepting a decrease in yields. Concern for environmental impact has also resulted in a general examination of the use of agrochemicals and how their use can be reduced. The jargon currently being used includes 'rational pesticide use' and 'integrated pest control' (Cousens *et al.* 1985). ('Pest' is used here to include weeds.)

Rather than make decisions arbitrarily, the intention is to help farmers to make considered judgments, bearing in mind all current information, and hence to remove much of the guesswork. The attitude encouraged is one of *management* of pest populations, taking actions based on a knowledge of how many are present, the likely effects of various husbandry practices and how best to control them in a cost-effective way.

We can consider three main categories of weed-management programs as follows.

(1) Eradication, where all possible efforts are directed against the weed species with the ultimate intention of its elimination. The emphasis is on the future, when control of the weed will be able to cease completely. Successes in eradication are limited to a few, widely quoted examples. However, some farmers have managed to reduce populations to very low levels where they are of little consequence. An example of this is control of wild oat (*Avena fatua* L.) by a combination of herbicides and hand-removal of survivors. Eradication programs are expensive, are seldom cost-effective in the short term, and are generally most feasible on newly introduced populations in small areas.

(2) Prophylaxis, where the intention is to attempt to avoid loss of revenue (or at least to minimize this loss) in every year. This is an insurance strategy, where herbicides are used every year regardless of the size of the weed population. Prophylaxis is almost the only option if major use is made of pre-emergence herbicides which must be applied before the weed flora is visible. Such blanket applications of herbicides are likely to be excessive, wasting chemicals and hence money. In addition, any routine application of a narrow range of chemicals is likely to encourage the development of resistant weeds. Prophylaxis is most likely to be justified if chemical costs are low, either in absolute terms or as a proportion of other costs, and if yield losses occur in most years (Matthews 1984). It will also be viable if there is a strong pressure to avoid the risk of losing yield.

(3) Containment, where the intention is to keep the weed population at or below a specific level. This involves acceptance of some level of yield loss, but in principle will result in weed control and expenditure only when truly justified. As a result, it is argued that this will be the most cost-effective and environmentally acceptable strategy. A containment policy presupposes that an appropriate weed population can be defined and that weed populations will be monitored to ensure correct decisions. Hence containment is inextricably linked with weed control thresholds.

In this paper the major problems associated with a containment policy will be addressed. Different definitions of thresholds and how to decide what levels of weeds are worth controlling will be examined. Published values of thresholds will be discussed. Emphasis throughout will be on single-species weed problems for which control decisions are made in their own right, regardless of the associated flora. The difficulties of applying thresholds to multi-species weed control will be discussed briefly. Various aspects of monitoring weed populations will be discussed, as will problems with the unpredictable behaviour of weeds. Finally, a very personal view will be given on the present state of affairs, on the usefulness of thresholds and the likely reactions of farmers.

Definitions of thresholds

In order to adopt a containment strategy it is necessary to define the level above which a weed population is considered unacceptable. This is far from simple and is not helped by an often vague and confused literature. Many papers simply refer to 'the threshold' without defining what they mean; others present a wide range of definitions, many of them vague. The question of how to define a threshold is far from semantic, since it is fundamental to weed-management strategy. We must understand what we mean before we try to put it into action. Also, depending on our particular definition, estimates of a threshold can vary by an order of magnitude. Since the threshold, however defined, is to be adopted as a guide for whether or not to take action, usually involving a spray application, the terms 'action' threshold and 'spray decision' threshold have been coined (Walker 1983; Wilson 1986). The various ways of identifying an action threshold will be discussed below.

1. Competition threshold. It is often argued that a few weeds cannot possibly affect yield, whereas a heavy weed infestation must have an effect. This has resulted in the suggestion that when all else is fixed, the relationship between crop yield and weed density is approximately sigmoidal, and hypothetical pictures depicting this are often shown (Zimdahl 1980; Koch and Walter 1983*a*; Utomo 1981) (Figure 1*a*). Indeed, it is often stated categorically that the relationship *is* sigmoidal (Roberts *et al.* 1982; Radosevich and Holt 1984; Radosevich *et al.* 1986). The weed density at which yield loss begins to occur has been referred to as the 'minimum critical population' (Wetala 1976), 'threshold value' (Moody 1983), 'competition threshold' (Cousens *et al.* 1985; Cussans *et al.* 1986), 'critical density', or 'damage threshold' (Fenemore 1984). Clearly, if such a weed density could be defined, then no yield loss would occur if populations could be constrained below it. It would be the obvious basis for an action threshold.

Graphical representation of data, however, seldom, if ever, shows any suggestion of a sigmoidal curve (Figure 1*b*.) (Cousens *et al.* 1984). Although Zimdahl (1980) has been quoted as observing a sigmoidal response (Radosevich *et al.* 1986), both Hakansson (1983) and Cousens (1985*a*) have pointed out that none of the data summarized by Zimdahl (1980) supports this. When large numbers of experiments are examined there is no evidence to support a general sigmoidal curve (Cousens *et al.* 1984). Of the many curves fitted to data (Cousens 1985*a*), only one is sigmoidal (Williams and Hayes 1984) and even this shows systematic lack of fit. The only supposed evidence for a sigmoid curve is from data analysed by multiple comparison tests (such as Duncan's multiple range test or the least significant difference) and not plotted. As many authors have pointed out, this is a misuse of statistics (e.g. Little 1981) and those same data, when plotted, clearly show a different picture.

The popularity of the competition threshold as a concept appears to result from the fact that experiments at low weed density will tend not to show any statistically significant differences in yield from a weed-free control. From this it is concluded that at low weed

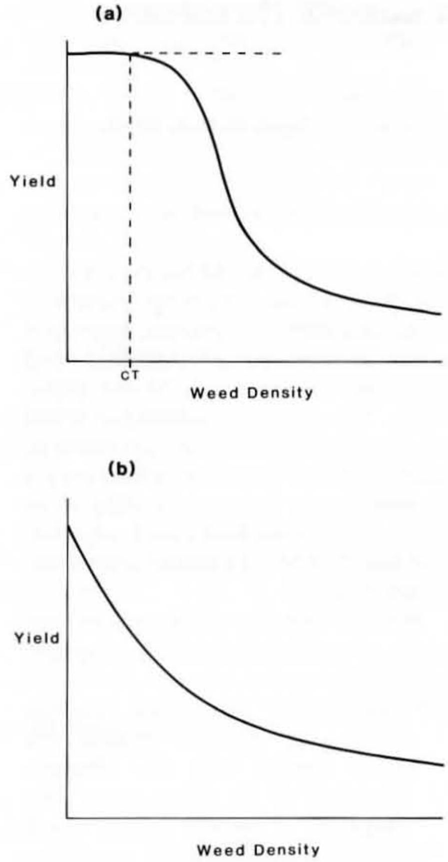

Figure 1 Yield response as a function of weed density: (*a*) conceptual sigmoidal response, showing competition threshold (CT) (after Zimdahl 1980) (*b*) usual observed response (Cousens 1985*a*).

density there is no effect of weeds on yield. Such a conclusion ignores the fact that in most field experiments even large real yield effects may not be statistically significant (Cousens 1985*b*). It is clearly unwise to conclude from a non-significant result that yield is unaffected by a few weeds. The only acceptable way to analyse a series of weed densities is through regression or some other curve-fitting procedure. When this is done and the data plotted, the curve usually concluded is hyperbolic in form (Cousens 1985*a*) with no competition threshold.

2. Statistical threshold. Many papers refer to a threshold at which statistically significant losses can be observed. This has been called the 'critical threshold level' by Mercado (1979) and Koch and Walter (1983*a*), the 'biological threshold' by Koch and Walter (1983*b*) and the 'critical density' by Weaver (1986). For the reasons stated above, this is not the same as the competition threshold below which no yield loss occurs. At the point at which significance is reached, the estimate of the yield effect is not zero and may be quite high (e.g. Coble *et al.* 1981). The lowest density at which a significant yield effect will be observed in an experiment depends on the number of treatments, the number of replicates, the structure and layout of the experiment, the variability of the data and the competitiveness of the weed species. The statistical threshold is thus only partly a biological quantity and to a large part is a reflection of the particular experiment.

It is thus highly doubtful whether a statistical threshold is of any practical use for weed management. In fact, in many competition experiments an economic threshold response (see below), even if it were to occur, would not be concluded statistically significant. The least significant difference, for example, is not only the level above which a difference is likely to be real, but is also the level below which a real difference of that size would probably be missed.

The methods used to calculate the statistical threshold reflect the confusion between the biological and statistical elements. As was mentioned above, the most usual, but incorrect, method is to use a multiple comparison test to compare all possible pairs of experimental weed densities. Coble and Ritter (1978) and Coble *et al.* (1981), however, fit a straight line to their data, which they show graphically to be reasonable. They then calculate the point at which the lower confidence interval for the weed-free intercept just meets the upper confidence interval for the fitted line (Figure 2). This is clearly a statistical threshold, but which they refer to as a 'damage' threshold. To conclude that at this point yield loss begins to occur would be to deny the obvious linear relationship used to calculate that point. Schweizer (1983) and Schweizer and Lauridson (1985) used a similar approach to calculate 'the minimum density required to reduce yields', but observed that the estimate of yield loss at this point was 8–12%,

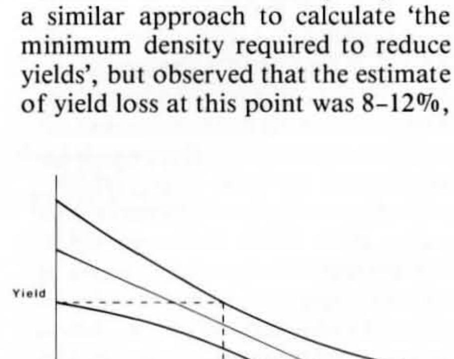

Figure 2 Method used to calculate statistical threshold (ST) from a linear regression (Coble and Ritter 1978).

not zero. There is clearly contradiction within such papers and a confusion in many papers where the statistical and competition thresholds are wrongly assumed to be identical.

3. Economic threshold. This is defined as the weed density at which the cost of control measures equals the increased return on yield which would result. At weed populations above this, control is clearly justified on economic grounds. In insect and disease studies this is often referred to as the 'economic injury level' (Stern *et al.* 1959) or less commonly as the 'damage threshold' (Walker 1983). A possible point of confusion is the interpretation of the economic threshold as the point at which economic losses start to occur and that treatment is needed to avoid loss of revenue (e.g. Matthews 1984). This is not the case, since any loss in yield will have an economic effect, no matter how slight, and this economic loss is increasing up to and beyond the economic threshold. It is only at the economic threshold that *control* measures become cost-effective, such that they produce a positive economic benefit.

Many simple models have been described for the calculation of economic thresholds (Chiang 1979; Marra and Carlson 1983; Beer and Heitefuss 1981; Mumford and Norton 1984). These are all intuitively obvious and assume a linear relationship between yield loss and weed or pest density. Also implicit is the assumption that maximization of profit is the same as maximization of yield. For most species where the crop is grown for consumption and not for seed, these assumptions are probably valid in the region of the economic threshold (Cousens *et al.* 1985). The models simply equate costs of control with increased return, e.g.

$$C_h + C_a = P \ H \ D^* \ L \quad (1)$$

where C_h and C_a are costs of herbicide and its application respectively, P is the price obtained for the produce, H is the proportion of weeds controlled, D^* is the threshold weed density and L is the loss in yield per weed plant, all in appropriate units (Marra and Carlson 1983). Cousens *et al.* (1985) extended this to allow for hyperbolic yield response curves:

$$C_h + C_a = PY_{wf}\left\{iD^*/(1+iD^*/a) - iD^*(1-H)/(1+iD^*(1-H)/a)\right\} \quad (2)$$

which simplifies to

$$1 + (D^*i/a)\left\{2 - H - YPaH/(C_h + C_a)\right\} + (D^*i/a)^2(1-H) = 0 \quad (3)$$

Table 1 Economic thresholds for *Avena fatua* in cereals. Values are taken from Cousens *et al.* (1985) and Auld and Tisdell (1986).

Competition *i* (m^2 plant^{-1})	**Coeff.** *a*	**Herbicide kill**	**Weed-free yield** (t ha^{-1})	**Grain price** (£ t^{-1})	**Herbicide cost** (£ ha^{-1})	**Economic threshold** (plant m^{-2})
0.01	1.0	0.9	6.5	100	45	8.41
0.02	1.0	0.9	6.5	100	45	4.20
0.005	1.0	0.9	6.5	100	45	16.82
0.01	1.0	0.9	10.0	100	45	5.9
0.01	1.0	0.75	6.5	100	45	10.46
0.01	1.0	0.75	6.5	100	25	5.48
0.01	1.0	0.9	2.0	100[A]	22[A]	14.15
0.01	1.0	0.9	1.5	100[A]	22[A]	19.93
0.01	1.0	0.9	5.0	100[A]	22[A]	5.17
0.01	1.0	0.9	5.0	150[A]	22[A]	3.38

[A]Values are in Australian dollars (Auld and Tisdell 1986).

where i and a are yield loss parameters and Y_{wf} is weed-free yield. This equation can be solved for the economic threshold by the familiar method for quadratic equations.

The economic threshold is not constant for a particular weed and crop combination. It can be seen that anything which is likely to affect any of the parameters will result in a different threshold value. For example, crop density will affect weed-free yield and the yield loss parameters. Reduction of herbicide dose (or selection of a cheaper herbicide) will affect herbicide performance and cost. Auld and Tisdell (1986) discuss some of the factors likely to affect economic threshold calculations. Hence, a statement that 'the economic threshold for control of *x* is *y* plants/m²'. (e.g. Anon. 1982) carries little meaning. It is necessary to specify all the assumptions for every calculation of an economic threshold. Table 1 shows economic thresholds for *A. fatua* in cereals, calculated under a range of parameter values. Assumptions about weed performance, herbicide performance and grain yield all have a large effect on the economic threshold. For most situations it is almost impossible to forecast accurately some or all of these parameters. There will also be a different economic threshold for every herbicide, since costs and effectiveness may vary considerably.

In almost all economic threshold calculations it is assumed that the only economic effect is through quantity of yield. Few data are available on the quality of yield and hence on sale price. This has been discussed by Cousens *et al.* (1985, 1986) and Auld and Tisdell (1986); in the examples so far studied, crop quality is unlikely to be important at the level of the economic threshold. If the crop is grown for seed, there may be a strong penalty for contamination by weed seeds and this may result in a much lower economic threshold (Auld and Tisdell 1986). Although reductions in the ease and efficiency of harvesting are usually a minor problem around the economic threshold level, a severe weed infestation may make the crop completely impossible to harvest in north European conditions. This has undoubtedly had a powerful effect on many farmers' perceptions of weeds. Elliott's (1980) study concerned only weed densities well above any threshold. Any of these factors other than yield, however, can be introduced into calculations if data are available.

4. Economic optimum threshold. Traditional economic threshold calculations assume that the economic effect of herbicide control is in the current year only. Costs and benefits are therefore equated in the year of application. It is well accepted that one of the major reasons for control decisions is the prevention of future population increases. Economic consequences of weed control therefore run into later years and will affect decisions then. Economic thresholds should therefore take population build-up into account. In order to do this, certain assumptions must be made concerning population dynamics and financial discount-

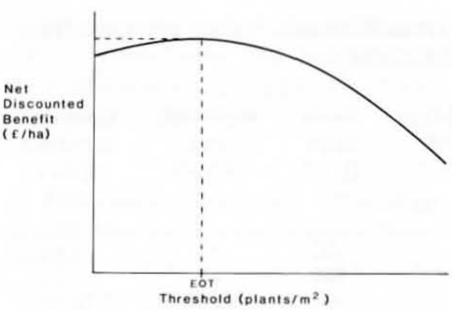

Figure 3 Relationship between net discounted benefit and threshold applied in simulations, showing the economic optimum threshold (EOT).

ing. Auld and Tisdell (1986) examined the effect of economics over a 2-year period on the economic threshold. Cousens *et al.* (1986) and Doyle *et al.* (1986) used empirical population models to examine economic effects over 10 years. By simulating the effects of adopting a range of spray thresholds over time, it was possible to identify the one which gave maximum profitability. The resulting curves (Figure 3) have a peak which has been termed the 'economic optimum threshold', in order to express the true nature of the calculation.

The appeal of such a threshold is that weed biology and dynamics are taken into account, avoiding the problems which make the traditional economic threshold uneconomic and naive as a decision rule. The drawbacks are the need for large quantities of data, not available for most species, and thereby the making of many more assumptions. For at least some species, however, they allow an estimate of the magnitude of the allowance which should be made for the effects of future weed populations. Cousens (1986) has compared the economic optimum threshold with the simpler approach of dividing the traditional economic threshold by the potential rate of increase of the weed.

5. Predictive threshold. In pest management, distinction is made between an 'economic injury level', at which losses will equal the cost of treatment, and an 'economic threshold' (or action threshold) at which control measures must be taken to prevent population increase to the economic injury level (Walker 1983; Stern *et al.* 1959). This is to cope with the fact that pest populations can increase greatly between the time of monitoring and the time of pesticide application and effectiveness. In most weed situations the two thresholds can be considered synonymous, since the generation time is very much greater than the time taken to carry out a decision. Many herbicides in winter cereals, for example, are used when most of the weeds have emerged, at a time of year when both weed and crop are growing slowly and at a point when little competition will have taken place. If pre-emergence herbicides are to be used, the potential weed population cannot be assessed easily.

For grass weeds, it may be extremely difficult to assess numbers accurately in a cereal crop until flowering. In such cases it may be considered reasonable to monitor numbers of grass-weed inflorescences in the preceding crop and to decide to spray to avoid some threshold being exceeded in the following crop. For example, spray decisions may be based on numbers of grass panicles in the preceding crop by reducing the economic threshold by an appropriate rate of population increase (Cussans *et al.* 1986). Cussans *et al.* (1986) point out that such prediction may be possible only in species with virtually no seed bank. In species with a high degree of dormancy and persistence in the soil, the present population (perhaps survivors from a recent spraying) may bear little relation to the population in the following year. For a predictive threshold data are required on population rates of increase; rates of increase, however, may vary enormously from year to year (Selman 1970).

6. Safety threshold. Most threshold calculations treat the parameters as deterministic, not subject to variation. All factors that we might wish to include can be subject to quite drastic and unexpected fluctuations. If the only aim of weed control is maximization of profit in the long term, then calculations based on the mean values may give an acceptable answer. Most farmers are also likely to aim to avoid disasters and would wish to include some element of risk aversion in their decisions (Auld and Tisdell 1986). If a mortgage is to be repaid, there is a need to guarantee a certain minimum income, even at the possible expense of some yield in the long term. In a 'bad' year, a decision not to spray may in fact result in considerable loss if the weeds are more competitive than on average; expenditure on a spray may be wasted if the spray performs badly. Reductions in herbicide dose, which may maximize profit in the long term, may result in an increased variance of herbicide performance (B. J. Wilson, unpublished data). There are therefore many reasons to take risk into account when calculating a threshold.

Although Auld and Tisdell (1986) discussed the possible effects of uncertainty of weed population density on economic thresholds, there appear to have been no specific attempts to incorporate risk in an objective manner. Intensity of risk aversion is likely to be personal to every farmer and difficult to quantify. Arbitrary reduction of the economic threshold by a 'safety margin' appears to be the only approach used to date (Cussans *et al.* 1986).

7. Visual threshold. Every farmer and advisor has his own intuitive feel for what looks bad and what looks acceptable. Most would be happy to take spray decisions on this basis alone and would not consider the effort worth while in making detailed density assessments. There is also a strong professional pride in the achievement of a clean field and a healthy crop, which may over-ride economic considerations. Advisors will tend to err on the side of spraying low populations, perhaps to avoid the possibility of losing the trust of the farmer. The decision is thus dominated by the question of what to spray with, rather than whether to spray. However, there is clearly a subjective visual threshold which is at present the most widely used form of threshold, but which is almost impossible to quantify. Experience with advisors, showing them economic threshold populations of *Avena fatua*, has suggested that this visual threshold is well below other thresholds. More research in the area of farmers' perceptions of weed problems should be encouraged, since this may dominate weed control decisions.

Comment

The intention of the preceding discussion is not to confuse an already muddled literature by the introduction of more jargon. The aim has been to emphasize how difficult it is to define what weed population justifies spraying, how many types of definition are currently in use under the same term 'threshold' and that there is no single, acceptable definition. The term 'damage threshold', for example, can mean at least three different things depending on the particular author. A great deal of caution must be used when consulting the literature, since it would appear that many discussions of weed-control thresholds are vague and contradictory. There is no practical need for so many definitions, but there is a need to recognize that many factors must be taken into account in threshold calculations, and not simply present-year economics (Stern 1973). Traditional economic thresholds do not make economic sense and are naive in almost all situations. Rather than viewing a threshold as a definite step in a biological or economic response, it should be appreciated that the threshold is a rather arbitrary, indefinite point on a smooth curve.

An opinion expressed by Professor R. Heitefuss in discussion at the 1986 European Weed Research Society symposium on Economic Weed Control is that a farmer does not need to know how an advisor's threshold has been defined, and a single term 'economic threshold' should be used, regardless of the factors which go into its calculation. This attitude may be acceptable in some cases; however, the more discerning farmers, who are likely to use thresholds, would probably like to know what factors are taken into account. If a farmer does not know that an 'economic' threshold also allows for an element of risk avoidance, he may be inclined to add on his own safety factor. More importantly, in papers addressed to scientists, we must be precise and unambiguous. An 'economic' threshold which includes allowance for many factors other than economics is likely to lead to confusion. Throughout the literature it is difficult to decide how particular authors have reached their threshold values. For these reasons, the present author prefers the use of the rather loose terms 'action' threshold or 'spray decision' threshold, accompanied by a list of exactly what factors went into them and how.

Published values of thresholds

Despite the widespread use of the term threshold and its acceptance as a concept, relatively few published values are available. Many competition studies are justified by the need to calculate economic thresholds, but yet do not present such information themselves. Little would be gained from an exhaustive survey of thresholds calculated for all crops and all weeds, and only a brief selection for grass weeds in cereals will be discussed here. Estimated values for the competition threshold will not be discussed, since there is little evidence to support its existence, and only minor attention will be given to statistical thresholds.

For *Alopecurus myosuroides* Huds. in winter wheat Eggers and Niemann (1980) quote examples where 10–20 plants m^{-2} produced no detectable (= statistically significant) loss in yield, 20–22 plants m^{-2} produced yield losses of 6–8%, with the economic threshold being reached at 20–55 plants m^{-2}. For management of weeds on an entire farm, Niemann (1986) applied a 'damage' threshold of 20 plants m^{-2} of *A. myosuroides* and 15 plants m^{-2} of *Apera spica-venti* (L.) Beauv. These thresholds apparently have elements incorporated into them to allow for weed build-up and risk (P. Niemann, discussion at European Weed Research Society Symposium on Economic Weed Control 1986). Aarts and Visser (1985) suggest spraying populations of more than 25 plants m^{-2} of *A. myosuroides* or 15 plants m^{-2} of *A. spica-venti*. Wilson (1986) suggests spraying *A. myosuroides* when populations exceed two heads m^{-2} and *Avena fatua* when they exceed 0.5 plants m^{-2} in the preceding crop; both thresholds allow for present-year economics and arbitrary factors for risk and population build-up. None of the above values are quoted with regard to any specific herbicide, even though herbicide price and performance have a major influence on the calculations.

Carlson *et al.* (1981) calculated an economic threshold for *A. fatua* with difenzoquat under average assumptions of 11 plants m^{-2}; with changes in the assumptions the threshold ranged from 4 m^{-2} to 19 m^{-2}. Doyle *et al.* (1986) and Cousens *et al.* (1986) derived economic optimum thresholds over a 10-year period of 7.5 plants m^{-2} for *A. myosuroides* controlled with isoproturon and 2–3 plants m^{-2} for *A. fatua* controlled with difenzoquat. These calculations were highly sensitive to assumptions about the herbicide. Fewer values for thresholds are available for other weed species. If the use of thresholds is to become more widespread, estimates will be required for all species under a range of conditions and for all relevant herbicides. Single values supposed to apply under all possible circumstances are likely to be treated with scepticism by farmers. At present, one of the major limitations is the scarcity of published information on herbicide performance.

So far, discussion has assumed that a single weed species is to be controlled and that this decision will not be affected by the presence of other weeds. For this to be a reasonable assumption there must be specific herbicides which will affect only the target species, such as in the case of *A. fatua*. However, *A. fatua* herbicides, other than difenzoquat, have considerable affect on other species. The choice of herbicide for *A. fatua* may well depend on the abundance of *A. myosuroides*; a herbicide may then be chosen which will control both species, even though its effect on *A. fatua* may be lower. Thresholds for such dual control do not appear to have been examined for weeds. Blackshaw (1986) has discussed economic thresholds for mixtures of a herbicide and an insecticide. It is clear that such thresholds will be highly dependent on the herbicide.

Commonly, dicotyledonous weeds occur in mixtures of many species and most herbicides have a broad range of action against them. Each herbicide, however, will not give equal performance against all species and may be entirely useless for some weeds. The great variety of dicotyledenous weeds and herbicides means that the analysis of whether or not to use which herbicide requires a computer. Programs for this purpose have been developed (Endacott 1985), though the internal details are not made explicit and the programs are as yet not widely available. For many factors, such as the competitiveness of individual weed species, data are extremely limited and guess-work inevitably enters the computations. For example, Aarts and Visser (1985) take economic thresholds for some species, then modify them by arbitrary factors according to ease of control in the current or following crops. As a result of lack of data, many gross simplifications must be made when estimating yield loss by these multi-species communities (Wilson 1986). To date, this has involved the establishment of relative competitive indices, such as 'crop equivalents' (Wilson 1986) or 'standard weed units' (Aarts and Visser 1985), which are multiplied by the number of each species and then summed. Since this therefore assumes no inter- or intraspecific competition between weeds, such calculations are only valid at low weed density. If the total summed value exceeds a certain threshold, then spraying is recommended. Little detail has so far been given on how these thresholds are currently established. Wilson (1986) calculates his mixed species threshold on the basis of the cost of an average herbicide and then reduces this by an arbitrary factor to allow for build-up. No account is taken, however, of the performance of the herbicides on particular weed species.

Clearly, the current approaches to the problem of multi-species weed control are naive and, though showing promise, have a great way to go and many difficulties to be overcome. In general, the power available from computers is being under-utilized at present. Future use of 'expert systems' for herbicide choice could be combined with much more complex algorithms for the effect of weeds on crops and herbicides on weeds. The desire to simplify calculations so that the approach can be appreciated conceptually by both scientists and non-scientists should not be a constraint.

Practical application of thresholds

Once a definition of a threshold has been selected and a value derived, this must be put into practice. In order to know when a threshold has been exceeded, some form of monitoring is required. Virtually no papers concerned with thresholds direct themselves towards consideration of this. However, monitoring is as important for a weed management program as is calculation of the threshold value. In order to advise a farm manager when weed control was required, Marshall (1985) conducted a survey of 6 points per hectare on a rectangular grid; at each point four quadrants of either 0.1 m^2 or 0.25 m^2 were thrown. This appears to be a similar sampling frequency to that used by other workers. The sampling frequency required for monitoring programs does not appear to have been examined statistically; present programs are thus arbitrary and are influenced by largely ergonomic considerations. Factors such as how accurate surveys need to be, how this is influenced by spatial distribution and density, and what the optimum date for monitoring is still need to be addressed.

In the project reported by Marshall (1985, and personal communication), spraying is recommended for an entire field when the mean weed density in the worst 25% of sampled locations exceeds a threshold. This apparently illogical advice is one way of allowing for risk aversion and weed patchiness. A farmer may be unwilling to lose all of the yield in part of his field even if the mean density over the whole field is below the threshold. Marshall's (1985) recommendations are only a guide to the farm manager, who may decide to ignore the advice for other reasons. B. J. Wilson (personal communication), in a large-scale study on a commercial farm, has found the manager to be willing to spray only the patches where these are large and clearly delineated, but there is some reluctance to use the approach on a smaller or irregular area. Niemann (1986) also recognized the patchiness of weeds, using thresholds and surveys to decide on which parts of fields to apply herbicides. Perhaps the ultimate extension of this would be to automate the system completely, whereby a sprayer is switched on only as a tractor passes over densities of weeds above the threshold (Haggar *et al.* 1983). This 'patch sprayer' has not been developed further.

Even when herbicide spraying is to be on a whole-field basis, recognition of the patchy nature of weed distributions can be important in applying thresholds. For example, if weeds have an aggregated distribution, such as the negative binomial, estimates of yield loss using the mean field density may differ markedly from estimates calculated on a quadrat by quadrat basis. This should be appreciated and incorporated into methodology in order to administer thresholds correctly. No study has done this to date.

There have been relatively few reports of attempts to manage weed populations according to thresholds, and only a minority of these have done so rigorously. Almost all discussion on thresholds has been conceptual and not based on practical experience. The study reported by Marshall (1985) has been in progress for 5 years and has encountered few problems, with the exception of an increasing *Bromus commutatus* Schrad. population in one area. Financial advantages of a containment policy over prophylaxis at present appear to be small. Niemann (1986) reports a 5-year application of thresholds in which spraying has been reduced by 65% with *A. myosuroides* remaining under control. Kees (1986) and Beer (1986) also recently reported 10- and 3-year studies respectively; neither discusses the economic advantage of threshold application. In an unpublished attempt to control an initially high density mixed *A. fatua* and *A. myosuroides* community according to thresholds (G. W. Cussans, personal communication), after 3 years *A. myosuroides* was still well above the threshold and a third species, *Bromus sterilis* L., was becoming strongly invasive. *A. fatua*, however, was then at a level close to the threshold. This experiment was abandoned at the closure of the Weed Research Organization. Even though advisors have been quoting threshold values to farmers for several years, there appears to be no record of farmers applying thresholds rigorously of their own accord. Application of thresholds, then, remains largely an untested idea.

Conclusions

Considering the widespread attention being given to weed control thresholds, both the theoretical and practical aspects are remarkably poorly thought-out. Many of those papers proposing the use of thresholds include loose and ambiguous terminology which is poorly defined. Many of the values proposed are either completely or partially subjective, derived from few data and are often based on fallacious statistics. Requirements for population assessment have yet to be considered. Perhaps the most surprising fact is that thresholds are at present virtually untried and untested; in any other industry the introduction of a radical (though logical) new approach would be preceded by in-depth feasibility studies, economic appraisals and field trials. This does not seem to be the case with thresholds. A sensible approach would be to hold back at this point and to make sure that this ground is covered before progressing too far. Few biologists or agronomists have a detailed knowledge of economics and they appear reluctant to do the necessary calculations. In addition, few economists have become interested in crop protection. If we are really serious about the use of thresholds in farming, then we must actively seek the participation of trained economists.

Weed-management and weed-control thresholds have, to date, been largely subjects of 'armchair' agronomy and have suffered from this. We would certainly be fooling ourselves if we considered our present approaches to be completely objective and logical. Areas that deserve special attention, and which are essential for putting thresholds into action, have been largely ignored. Calculations, which begin by being rigorous, end in subjective and arbitrary safety factors in order to bridge the gap between very limited theory and reality. In which case, are the values being derived any more useful than intuitive guesses? Has the field of thresholds taken on a respectability to which it is not, as yet, entitled? Indeed, could it be that thresholds are simply an academic toy, of no practical importance?

Two studies of the long-term economics of weed control (Doyle *et al.* 1986; Cousens *et al.* 1986) have found little financial benefit in the long term from applying the economic optimum threshold as opposed to applying another threshold of the same order of magnitude. Many farmers would not use extreme prophylaxis in any case, and the difference in benefit from thresholds as against their own arbitrary approach may be minor. It would appear, therefore, that there is little importance in being exact in the calculation and application of thresholds. Perhaps, then, the single-year economic threshold can be considered as a base-line, and we can choose our action threshold at some arbitrary point below this. A farmer may well err on the side of caution whatever value he is given, and may always prefer a lower value. A degree of subjectivity may not be important in the long term. In which case, is there any need for accurate assessments of population density? Provided that a subjective visual threshold is lower than the economic threshold, which remains to be shown, this could be sufficient and will save money spent on monitoring programs. Perhaps this could be aided by advisory photographs of economic threshold populations. Since we might then conclude that all we need is a farmer who is aware and thinks about his spray decisions, albeit using intuition, are thresholds necessary at all?

The arguments in favour of thresholds at this point become somewhat tenuous. Perhaps the most important point is that knowledge and understanding of thresholds will at least bring a small amount of objectivity into what will always be a largely subjective decision. The establishment of a base-line will be useful to advisors who need to become more knowledgeable on a particular problem. More important than the thresholds themselves, however, are the competition, population dynamics and herbicide performance data which can be used to calculate the financial implications of any decision. A farmer, for example, might find it helpful to know which of two options may give him a considerable benefit over the other, rather than 'the threshold is x m^{-2}'. It is far more important to obtain sufficient fundamental data on yield effects, such that such calculations can be made with confidence, than to pull a threshold value out of a hat. Much basic information is required on competitiveness of different species, variation in their density responses and population dynamics, and quantitative studies of factors affecting herbicide performance in the field.

It is surely misleading to quote an exact threshold value to a farmer, since it implies a precision which is not really there. It is apparent that discussion of thresholds, even by agronomists and scientists, has become cloaked in a false sense of objectivity. Subjectivity is acceptable in decision making and we should be honest about its presence.

Acknowledgments

Perceptive readers will notice the strong similarity between this and other papers by the same author, G. W. Cussans and B. J. Wilson. The ideas presented are not new and have been developed steadily over the past 3 years. However, much of the emphasis in the present paper is a personal interpretation by the author and may not reflect the exact feelings of his coworkers. Discussion and criticism by G. W. Cussans has been invaluable.

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