PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Weed Management: Fact or Fable?

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Weed management: fact or fable?

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Weed management is a new term for the age-old practice of employing all available means, in a planned way, to keep weed populations under control. It seeks to distinguish the systematic approach to weed control, based on scientific knowledge and rational strategies, from the pragmatic destruction of weeds. The remarkable efficiency of herbicides has in recent years emphasized the latter and allowed revolutionary methods of crop production to be practised. These have, however, led to serious new weed problems which in turn require more intensive herbicide use. The need for a weed management approach is increasingly recognized. New opportunities for this are provided by the availability of numerous herbicides and plant growth regulators and a growing understanding of the biology, ecology and population dynamics of weeds in relation to crop production systems. Examples discussed include: systematic control of grass weeds in intensive cereals in Britain, weed control in rice and in soybeans, the control of aquatic weeds by biological and chemical methods and an experimental zero-tillage cropping system for the humid tropics based on herbicides, growth regulators and ground-cover leguminous crops. In such management systems, interference of weed behaviour by exogenous growth regulators is likely to be of increasing significance. Constraints on the adoption of weed management practices include lack of support for weed science as a discipline, limited appeal to the agrochemical industry and inadequate extension services in many countries.

1. Introduction

In recent years the resilience of weed populations to intensive herbicide use, the increasing cost of chemical treatments, environmental issues and other problems have encouraged research workers to explore more systematic approaches to weed control. One result has been the emergence and widespread adoption of the term ‘weed management’. Many people, however, have little idea of what it means and what, if any, promise the underlying concept holds for the future. This symposium provides a timely opportunity to examine whether there is any substance to this new piece of jargon in offering a route to significant advances in weed control technology, and if so what the implications are likely to be for the future development of crop protection chemicals.

2. What is ‘weed management’?

Broadly speaking, approaches to weed control fall into two classes: (i) procedures for destroying weeds already present or about to grow in a field, and (ii) cultural methods for suppressing or avoiding weeds. Examples of the former are hand-weeding, hoeing, ploughing, burning and herbicides. The latter consist of the many and varied ways by which farmers attempt to cheat weeds – or at least to live with them – by practising the art of ‘good husbandry’. It may also appropriately include biological control. When discussing ‘weed management’ it is important to remember that, in farming, ‘agents of weed destruction’ seldom work in isolation and that many other factors influence the success of both control measures and weed populations. These factors may or may not be under the control of the farmer. If they are, they can perhaps be harnessed or manipulated to favour the crop or discourage the weeds, or both. Competition between crop and weed is a good example and there is much wisdom in the old saying, 'the best weedkiller is a good crop'.

Before the introduction of herbicides, weeds often dictated what crops could be grown. During the past 30 years, the ever-increasing range of selective herbicides has provided, for those in a position to use them, a new dimension of weed control efficacy that has enabled many time-honoured and previously essential husbandry practices to be abandoned in pursuit of greater efficiency and profitability in crop production. The cost and limited availability of labour, specialization in farm enterprises, heavy investment in plant and machinery and larger farming units have in any case restricted the farmer's freedom to change his system when weeds threaten his crops. While most people know that the introduction of new technology into agriculture has resulted in a vastly increased supply of food for the expanding world population, few realize that this revolution in crop production has been made possible by the ability of herbicides to kill weeds effectively, cheaply and safely in the growing crop, almost regardless of the method of husbandry employed. Thus crop rotation has been reduced or eliminated. The ability of herbicides to kill weeds without soil disturbance has allowed crops to be grown with greatly reduced soil tillage or without cultivating the soil at all. This trend is bound to continue as the cost of energy rises.

How have the weeds reacted to the joint impact of routine spraying with potent herbicides and the fundamental changes that have occurred in the management of land and crops?

In temperate agriculture, many weeds of arable land that were formerly of great importance when traditional husbandry was practised are now of little consequence. Examples are *Sinapis arvensis* and *Papaver rhoeas*. Others have, however, proved well suited to modern methods of crop production and in spite of the herbicides available for their control have become serious and intractable problems, as reviewed by Fryer (1979). Grasses like *Avena fatua*, *Alopecurus myosuroides* and *Agropyron repens* are now among the most important weeds of temperate cereals. In fruit and other perennial crops, herbicides have largely replaced soil cultivation, and perennial weeds like *Convolvulus arvensis* and *Cirsium arvense* are a major problem. In nothern Europe, crop plants themselves have become serious weeds in intensive production systems, for example, volunteer potatoes, volunteer cereals and weed beet (an annual form of sugar beet).

In developed agriculture in the tropics, similar changes have taken place involving different species but leading to analogous problems.

While herbicides have provided an immensely powerful tool for weed destruction, their very efficiency has enabled intensified systems of husbandry to be practised, which themselves have generated serious new weed problems requiring in turn more complex and expensive herbicide treatments. In such systems, reliance on herbicides for weed control has tended to become absolute.

Although it would be quite incorrect to give the impression that herbicides are failing to do the job for which they have been designed, their ability in experimental work to provide reliable and complete weed control may not reflect what can actually be achieved in farming practice. For example, efficacy may vary according to the weather and soil conditions; the cost of appropriate treatments may be more than the farmer can afford; the products may not be obtainable because of import or regulatory restrictions; appropriate application equipment may be lacking; the high level of skill and knowledge on the part of the farmer or his adviser may be insufficient to obtain the required performance.

Questions now being asked are: Has reliance on the empirical use of herbicides as a substitute for the mechanical and cultural methods of weed control formerly practised gone too far? Might not greater efficiency and cost-effectiveness in crop production be obtained if cultural and chemical methods of weed control were to be harnessed more positively to work together? By a better understanding, through research, of the weeds themselves, of their ecology, of the constraints that they impose on crop production, and of the factors influencing population trends in particular cropping régimes, could not a more rational approach to weed control result in greater economy in the use of chemicals and improved environmental quality or, where herbicides cannot be used, in more efficient weed control, higher yields and better use of human and other resources? If the answer to these questions is 'yes', then the introduction of a term like 'weed management' is certainly justified, to distinguish between (i) the empirical and often uninformed application of physical or chemical techniques to control weeds in a particular crop ('weed control') and (ii) the rational deployment of these measures in conjunction with appropriate cultural and husbandry practices to provide systematic weed control both in individual crops and in a cropping system over a period of years ('weed management'). The latter term also implies that both the tactics and the strategies employed are aimed at meeting specific objectives of the farmer and are based on a scientific understanding of the response of individual weeds and weed populations to changing cultural practices and specific control measures. A further refinement, implicit in the terms 'integrated weed management' or 'integrated pest management', is that the control of weeds should, if feasible, be integrated with requirements for protecting crops additionally from pests, pathogens, nematodes and other injurious organisms and undertaken with a knowledge of the interrelations between weed populations and these organisms. Shaw (1980) recognized four elements of integrated pest (weed) management (i.p.m.) research: basic research; control components research; systems research, level one (integration of control techniques for one or more weed species); systems research, level two (integration of management systems to provide control of weeds *and* other organisms). For the effective application of i.p.m. systems in practice he emphasizes the need for the research to be accompanied by appropriate programmes of extension and education.

In the rest of this paper some examples are given of progress towards the development of practical weed management systems, which it is hoped will add a touch of realism to the description already given and indicate the role that herbicides and plant growth regulators in this context may play in the future.

3. Control of grass weeds in British cereal growing

With the advent in the 1950s of selective herbicides for the control of broad-leaved weeds in cereal crops, and the introduction of combine harvesters, farmers in the main arable areas of England and Scotland found that they were able to grow successfully repeated crops of spring barley. Some abandoned crop rotation altogether. In these circumstances the rhizomatous grass weeds *Agropyron repens* and *Agrostis gigantea* flourished and became a major constraint on the ability of farmers to continue near-monoculture cereal cropping. The herbicides then available, and also the traditional practice of repeated between-crop cultivations, often failed to provide the required control, and insufficient was known of the reasons to allow convincing explanations or advice to be given. Seeking a solution, the Weed Research Organization undertook an intensive investigation of these weeds. Particular importance was attached to finding out how and when new rhizomes are formed under different cropping and cultivation régimes and how they respond to fragmentation by cultivations and to herbicides. It was found that maximum new rhizome growth occurs immediately before and after cereal harvest, and that exhaustion of both dormant buds and nutrient reserves of fragmented rhizomes after cultivation can quickly be realized so long as the buds are stimulated into growth and aerial shoots are not allowed to develop more than three or four leaves (Cussans 1970). This and the other information gained was followed up in a programme of nationwide agronomic experiments that demonstrated conclusively that these weeds could readily be controlled by a systematic régime of early post-harvest cultivations with or without associated herbicide treatment. Cereal farmers quickly put into practice what had been learned, with most successful results. This provided a striking demonstration of how research on the 'agroecology' of a weed could lead to the development of highly successful control strategies that contrasted with the poor performance of herbicides and cultivations when used empirically.

This work also had relevance to perennial grass weed problems in fruit crops which had been exacerbated by the widespread adoption of non-tillage practices after the introduction of simazine and paraquat. Since there was no effective herbicide treatment for these once plantations became established it became clear that a grower should, before committing his land to a perennial crop and the high investment that this involved, take steps to eliminate perennial weeds during the sequence of preceding annual crops. The investigation just described showed how the job could be done. This was another early practical example of weed management by which forethought, guidance from research, and investment in suitable control measures in a crop cycle, albeit uneconomic in terms of the particular crops treated, could pay dividends at a later stage, perhaps several years later.

Hard on the heels of the perennial grass weed problem in intensive cereals came a massive upsurge in populations of annual grass weeds, of particular importance being *Avena fatua* and *Alopecurus myosuroides*. Although several effective herbicides became available for their control during the 1970s, these weeds continued to spread within cereal-growing areas of the country and their population in individual fields was often maintained or even increased in spite of complex annual spraying programmes. In recent years, these and other grass weeds like *Poa trivialis* and *Bromus sterilis* have been exacerbated by the widespread growing of winter barley, and the replacement of ploughing by tine cultivation and direct-drilling. The cost and logistic problems of controlling these grass weeds, in addition to the inevitable dicotyledenous weeds, exclusively by herbicides has become an increasing cause for concern by farmers, accentuated by the recent decline in farm profits.

Encouraged by the earlier success of a 'weed management' approach to the control of *Agropyron repens* and *Agrostis gigantea*, the Weed Research Organization embarked in the early 1970s on a long-term interdisciplinary investigation of *Avena fatua*, the major wild oat species in Britain. A primary aim was to identify and quantify the factors controlling its success as a weed in the context of modern cereal growing in Britain. This information, coupled with a detailed knowledge of the performance of appropriate herbicides, would then be used to formulate tactics and strategies for its control or eradication tailored to suit specific farmers' requirements. A simplified model of the population cycle on which the planning and interpretation of the work was based is shown in figure 1.

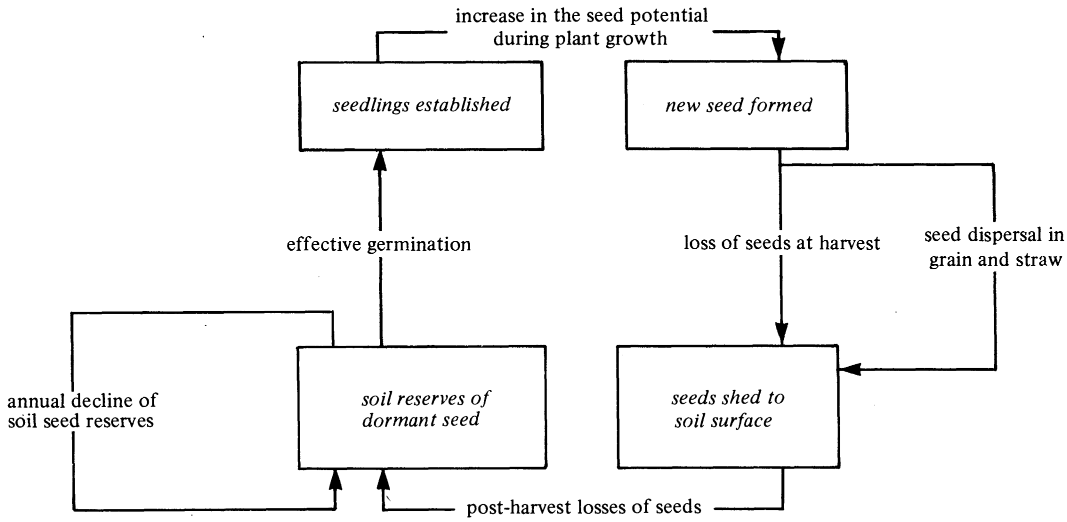

FIGURE 1. Schematic population cycle for wild oats.

The information gained during the past 10 years has been reviewed by Wilson (1981). It is very extensive and only one or two examples can be given here as an indication of its practical value.

In both winter and spring cereals, early emerging wild oats have been found to be not only the most competitive but also to produce the most seed. Priority in the application of control measures should therefore be given to treatments that are the most effective against these plants. Wild oats emerging later are less likely to reduce yield but will contribute to seed production unless steps are taken to prevent this. A significant result of the investigation was to show the advantage of using a programme of herbicide treatments compared with the conventional single application. For example, an early treatment of winter wheat with a half dose of herbicide sufficient to prevent competition followed by a later application of another herbicide, also at a reduced dose, to prevent production of wild oat seeds can be more efficacious than a single treatment of either herbicide at the full recommended dose in terms of weed control, seed return and improved crop yield (Wilson & Cussans 1978).

A great deal of other helpful information on herbicides has been obtained by research to identify and quantify the main factors governing their performance including application techniques, formulation and the climate (Fryer 1980).

Wild oat plants shed viable seeds before maturity and the degree of shedding is determined by the dates of emergence of the weed and of planting and harvesting the crop. An early harvest will increase the proportion of wild oat seeds removed from the field in straw and grain and hence the risk of spreading the weed to other fields (Wilson 1970). In late-harvested crops, more seed is shed on to the soil surface where its fate is crucial in determining the level of future infestations and the number of seeds in the soil bank. The W.R.O. programme has shown that the longer the field is left uncultivated after harvest, the greater is the loss of viable seeds, possibly from predation by birds and rodents, premature sprouting and microbial attack (figure 2). Straw burning is also important in determining the fate of shed seeds. It may kill them directly or break dormancy so that a larger proportion of shed seeds germinate before the next crop is sown or in the crop itself and can be eliminated if suitable control measures are taken. An example from a field experiment with spring barley is given in table 1. Such informa-

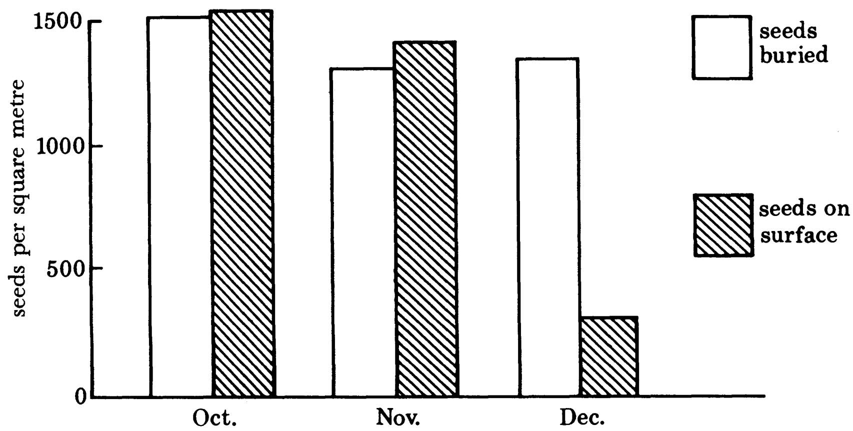

FIGURE 2. Recovery of viable seeds of *Avena fatua* from soil surface of stubble after shedding in a spring barley crop (Wilson 1972).

TABLE 1. EFFECT OF STRAW BURNING AND STUBBLE CULTIVATIONS ON *A. FATUA* IN SPRING BARLEY (WILSON & CUSSANS 1975)

	not burnt	burnt
viable seeds on stubble (September)	4345	2944
autumn seedlings after stubble cultivations	141	350
autumn seedlings on uncultivated stubble	31	102
spring seedlings in crop	594	433
seeds in soil (June)	1068	718

tion has proved most helpful to farmers in deciding their tactics for suppressing wild oat populations and in formulating their cropping strategy, e.g. spring-sown or winter-sown cereals.

Clearly, any chemical treatment that influenced either the time of shedding or the behaviour of seed after shedding, particularly its dormancy, could be a potent weapon to reduce wild oat populations, irrespective of its inability or otherwise to kill the mother plant. An important recent development in this investigation is a long-term study of the biochemistry and ultrastructure of dormancy and abscission mechanisms in the wild oat. It is hoped that this research (Osborne 1980) will identify both how these mechanisms can be disturbed and the nature of novel chemical compounds that might be effective. The possible use of ethylene to stimulate the germination of dormant seeds in the soil has already been referred to by Chancellor (this symposium).

An enormous amount of information has been obtained on the biology and agroecology of wild oats and their response to herbicides and other control measures. That this has provided the basis of a National Wild Oat Advisory Programme, supported by all organizations in the U.K. concerned with crop protection, is an indication of its value in practical terms. While cropping practices and economic values may change, the knowledge that has been gained of the biology of this weed and of the factors determining population changes and the efficacy of control measures will continue to allow the subjective judgements by farmers and advisers, inherent in any weed management programme, to be more informed than was previously possible. Much, however, remains to be done to maximize the use to which this information can be put, and predictive modelling will undoubtedly have an important part to play. Cussans (1976) has provided some indication of the value of this approach. He calculated from available data that, for example, if the annual use of a herbicide treatment in continuous spring barley results in an 80% reduction of viable wild oat seeds shed (a result judged by many farmers to be highly successful), the population of wild oat seeds in the soil and hence future levels of infestation will continue to increase as long as the farmer tine-cultivates the field soon after harvest. In contrast, if the post-harvest cultivation is omitted and ploughing is delayed until December, a slow decline in the seed bank will take place and the problem will diminish year by year.

Much thought is currently being given to how further use might be made of the extensive data available to allow improved strategies and predictive models to be developed and validated by a combination of whole-field or whole-farm monitoring exercises and further component research. Unfortunately, the limited resources available for such work make rapid advance unlikely, particularly when it is realized that wild oats seldom grow in isolation but interact with other important weeds such as *Alopecurus myosuroides*, which may respond differently to control measures. While progress is being made in integrating the requirements for controlling mixed populations of weeds, the recent appearance of *Bromus sterilis* as a major weed in winter barley grown in reduced-tillage systems is unfortunately placing urgent demands on the research workers who might otherwise have been refining and developing the wild oat programme. Relevant experience is, however, being gained in the development of computer modelling as a tool for predicting population changes in other weed species (Mortimer *et al.* 1980).

Research of the type outlined has re-emphasized that plants can only be weeds when their behaviour is well adapted to the ecosystem resulting from the farmers' endeavours to grow crops and they can tolerate the control measures that he takes. A change in either may quickly alter their status as weeds. To kill them physically by mechanical, chemical or any other means is not the only approach that will lead to the diminution of a weed population. To alter the ecosystem, e.g. by introducing crop rotation or modifying tillage régimes, may or may not be feasible for the modern farmer but is a potent long-term weapon wherever it can be employed. Potentially effective also is any means by which the behaviour of the plant itself is modified so that it becomes less suited to the farming system in which it is a problem. Thus synthetic plant growth regulators able to influence the dormancy and shedding of seeds or the behaviour of buds and meristems should be viewed as potentially powerful agents of weed management. In the meantime the work already undertaken has led to a much better knowledge of some of the most important weeds of British cereal growing and an enhanced ability on the part of the farmer (i) to plan and execute management tactics within a prescribed cropping system, and (ii) to consider the consequences of major changes in husbandry strategy in terms of the weed populations that he is likely to encounter and the cost and technical problems associated with their control.

4. Examples of weed management overseas

Weed management in rice

Traditional methods of growing rice have depended very heavily on the value of flooding in suppressing weeds. For instance, farmers in many parts of Asia wait until the land is inundated by accumulated rain or floods in mid-season before establishing a single transplanted crop. A

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layer of water almost completely suppresses the germination of the most competitive weed species. These farmers are now being encouraged to increase productivity by growing two crops per year. These new procedures for double cropping, and in other regions reduced labour availability for transplanting, are leading to an increased acreage of direct-sown rice in which weeds are a much greater problem. When rice is sown into dry soil like a temperate cereal, it may take up to seven times the number of manual weeding hours needed by paddy rice.

While weeds in rice are still controlled mainly by hand-weeding, herbicides are being used widely and where the use has been more intensive some more tolerant annual and perennial species have become important. The simplest method of preventing and perhaps overcoming such problems is to follow herbicide use by hand-weeding to destroy survivors and prevent their build-up (Parker 1977). Farmers have to be persuaded that this is worth while, so education and extension are vital ingredients of weed management programmes.

While detailed research has yet to be undertaken to determine and quantify the factors responsible for population changes in many weeds of rice, workers at the International Rice Research Institute and elsewhere are vigorously supporting the introduction of weed management approaches. These embrace a range of complementary agronomic practices and direct control measures (Moody & de Datta 1977; Noda 1977). Examples of the former are: land preparation (including delayed planting so that successive flushes of weeds may be destroyed by cultivation or herbicides); water and fertilizer management; choice of competitive rice cultivars; planting density; post-planting cultivations. Crop rotation is, as always, a potent weed control tactic and indeed may be the only means of controlling such hard-to-kill weeds as red rice (*Oryza sativa* L.). Of the direct control measures available, hand-weeding, inter-row hoeing and herbicides are the most commonly used. In Japan, the Tadpole shrimp (*Triopus* spp.) introduced at a density of 20–30/m^2 has provided effective biological control of weeds in transplanted rice (Matsunaka 1976). In highly mechanized rice production, as in the U.S.A. and Japan, integrated control systems are being found necessary even for weeds, such as *Echinochloa crus-galli*, that are susceptible to herbicides. The components of such a system are illustrated in a simplified version (figure 3) of the model developed by Noda (1977) for control of this species in Japan.

Weed management in soybeans

The dependence of British cereal growers on herbicides has already been mentioned. A comparable example is the soybean crop in the United States, for which, by 1978, 30 individual herbicides had been registered for use in the crop together with an additional 60 combinations (Shaw *et al.* 1979). Earlier, Wax (1977) had expressed optimism that further developments in herbicides offered much promise for continuing to provide the required level of weed control despite the introduction of husbandry practices such as reduced tillage, double cropping, use of semi-dwarf varieties and narrow rows which, while improving crop productivity encouraged weeds. Nevertheless, Shaw *et al.* (1979) reported that even when the most effective weed control technology is used there are still serious weed problems that remain unsolved in all the main regions of the United States in which soybeans are grown. The authors conclude that progress in the future must depend on the development of research-based weed management systems involving the most sophisticated use of herbicide technology in combination with agronomic practices. It has for instance been shown that although *Sorghum halepense* cannot be easily controlled by herbicides in a single season, it can be suppressed by the use of trifluralin at a higher than standard dose for two successive seasons (McWhorter 1974). A more recent development,

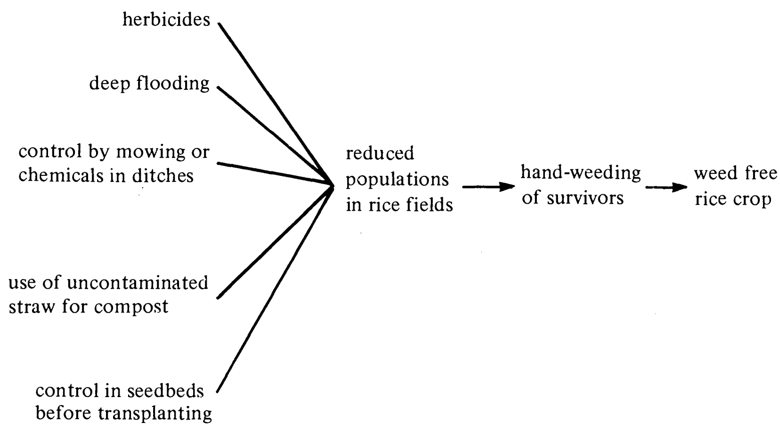

FIGURE 3. Model of integrated approach to control of *Echinochloa crus-galli* in rice fields in Japan (adapted from Noda 1977).

substituting for the supplementary hand-weeding which is otherwise desirable, has been the use of 'rope-wick' applicators to control weeds emerging above the crop in mid-season. That good progress is being made is evident from Slife (1980). Much relevant and valuable experience is already available from a long-term field experiment begun in 1964 by the University of Illinois, Agronomy Department, in collaboration with the United States Department of Agriculture. In this the influence of crop rotation, tillage levels and methods of weed control on weeds and weed seed populations has been measured year by year and related to crop yields (Slife & Wax 1976). The cropping systems selected for study are: maize, soybeans and wheat, each grown in monoculture; maize, maize, soybean; maize, soybean, wheat. Research on the mechanisms controlling the changes in population of individual weed species in the different cropping systems is in progress.

Aquatic weed management

Agriculture in much of the world is dependent on adequate drainage or irrigation with their associated rivers, channels and lakes. The latter also of course provided an important amenity for recreation and serve as a habitat for fish and other wildlife. Water storage on a vast scale is also needed for hydroelectricity schemes and urban and industrial water supplies.

The proliferation of aquatic plants often threatens the many functions of water systems, and in addition may harbour vectors of diseases. The traditional methods of control involve much manual labour and nowadays may no longer be applicable. Even where labour is cheap and abundant the sheer scale of aquatic weed problems may defy effective action, for example *Eichhornia crassipes* in the Nile and Zaire rivers, *Salvinia* spp. in Africa, India and Sri Lanka and *Hydrilla verticillata* in the U.S.A., Panama and other areas.

Herbicides provide a new tool for the control of aquatic vegetation and have been extensively used, often with great success. But there are many shortcomings and difficulties. A common problem is that as susceptible macrophytes are killed their place is quickly filled by tolerant species that can prove more troublesome than the original vegetation and moreover prevent the recovery of the disrupted ecosystem.

The elimination of all plant life is only occasionally acceptable, as with industrial plants and certain types of irrigation channels. Generally the aim is to control the vegetation sufficiently for the channel or lake to function properly while at the same time maintaining sufficient plant cover to prevent erosion and where appropriate provide a habitat for aquatic organisms. To achieve this is often difficult and sometimes impossible for technical or economic reasons.

There seems general agreement among specialists in this field that advances in aquatic weed control must be based on a weed management approach, implying a knowledge of the ecosystems involved and the rational deployment of whatever control measures are available and feasible. In addition to hand, mechanical and chemical methods, biotic agents are receiving much attention at the present time, notably the Chinese grass carp (*Ctenopharyngodon idella*), a herbivorous fish. In Russia and Eastern Europe its introduction has been primarily as a source of food, and weed control has been incidental, whereas in the Netherlands, Britain and the U.S.A. its potential for controlling aquatic weeds is the main interest (Robson 1977).

In field experiments in the Netherlands, considerable success has been achieved by introducing grass carp into drainage systems, and the fish is considered to be an effective tool for aquatic weed management (Zon 1979). There are, however, many problems, particularly in matching stocking density to suit its feeding habits, the seasonal growth of the aquatic plants and the amount of vegetation to be consumed. Moreover, their preference for some species and dislike of others may at low stocking rates lead to the total biomass of the plant population being maintained (Fowler & Robson 1978). The timely application of herbicides or of mechanical control measures is likely therefore to be an essential adjunct to the use of the fish. The same holds true for other predators that can be harnessed for aquatic weed control, such as the moth *Paraponyx stratiotata*, which feeds on *Myriophyllum spicatum*, the flea beetle *Agasicles hyrophila* on *Alternaria philoxeroides*, and a range of insects that have shown potential for controlling *Eichhornia crassipes*.

Another biotic approach to the management of aquatic weeds is to attempt to replace them by low-growing highly competitive species. As unlikely as this sounds, considerable success has been achieved in California by the use of spikerush *Eleocharis* spp. These form large, lawn-like mats under water under suitable conditions and prevent the roots of young, floating macrophytes from anchoring in the bottom soil (Yeo 1980). Promising results have also been obtained by Mehta & Sharma (1975) in Rajasthan, India, by planting paragrass (*Brachiaria mutica*) in drainage ditches to control the troublesome weed *Typha angustata*. While the paragrass is itself sufficiently tall-growing to block the channels, it is, unlike *Typha*, valuable for fodder and so attracts regular cutting for this purpose.

A recent development of great relevance to aquatic weed management is the application of the herbicide diquat in the form of an alginate gel into flowing or static water for the local control of aquatic weeds. This technique pioneered by Barrett (1978) allows channels to be cut through weed beds in rivers by killing the vegetation in a narrow band downstream of the application. In lakes, local clearance of vegetation can also be obtained at selected sites to facilitate fishing or boating, while causing no damage to the untreated areas. Since the method does not result in contamination by the herbicide of the water body as a whole, it is proving much more acceptable to those concerned with pollution and other undesirable side effects than conventional ways of using herbicides.

Looking into the future, there seems considerable scope for the further development of herbicides and perhaps particularly of growth inhibitors for aquatic weed control used as weed management tools with or without associated bio-control or mechanical methods. Unfortunately the market is small and the development costs formidable, so this area of use for crop protection chemicals is likely to remain unattractive to industry.

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Weed management as a key to novel non-tillage systems for small scale farmers in the tropics

Wijewardene (1978, 1980) has forcefully pointed out that mechanized systems of farming as practised in developing countries can compare very unfavourably with traditional crop production in the tropics when judged by the ratio of yield to energy input, although actual yields per unit area of land are usually much higher. As a result of work at the International Institute of Tropical Agriculture (I.I.T.A.) in Nigeria, he postulates that the route to greater productivity for small-scale farmers in the tropics lies not in the adoption of conventional mechanization and high inputs but in developments based on slash and burn agriculture, the age-old system for growing crops without cultivating the soil. In this, forest trees are felled and burned and the crop is planted directly into the bare soil, fertility being provided by the wood ash. After one or more years, weeds and reduced fertility make it impossible for further crops to be grown so the farmer moves on to another site. If the vegetation could be controlled by herbicides it might then be possible to grow more crops on the same site, provided that fertilizers were used or leguminous plants grown to fix nitrogen. A farmer would then be able to manage a larger area of crops and the land could support a higher population. In trials at I.I.T.A. and more recently in Sri Lanka, Wijewardene has put these ideas into practice, developing special machines for 'jab planting' the crop seed directly into uncultivated soil and using simple spinning disc sprayers to apply herbicides at the very low volume rate of 20–40 l/ha to control both herbaceous weeds and regrowing trees and shrubs. Recently Akobundu (1980) has reported an interesting development of this technique, which entails planting an area, after the initial clearing, with a leguminous cover crop such as *Arachis repens*, *Centrosema pubescens* or *Psophocarpus palustris*. After this has established paraquat is sprayed to clear 15 cm strips into which maize is planted. The cover crop not only suppresses weeds but fixes nitrogen. In a preliminary experiment the yield of maize grown in this way without additional fertilizer exceeded that when maize was grown conventionally with applied nitrogen at 60 kg N/ha. Management of the cover crops is a key element in this technique and promising results have been obtained with a growth regulator (CGA 4283) applied to the more vigorous legumes to stop them from overrunning the maize plants.

This system, as yet in the early pioneering stage, holds much promise for increasing both food production and living standards for small-scale tropical farmers without recourse to major capital expenditure. It is simple in concept but potentially vulnerable to weeds that prove to be beyond the capabilities of the farmer to control, and much more experimental and development work will be needed before the practical feasibility of the system can be judged. If it can be made to work by small-scale farmers in the humid tropics, the potential outlet for herbicides, growth regulators and other crop protection chemicals could be enormous.

Conclusion

It is clear from this brief survey that many trends in modern agricultural practice favour the development of serious weed problems. Provided that the profitability of a farming system remains high, farmers will often be content to rely on herbicides, and herbicides alone, for their weed control in countries where appropriate products can be readily obtained and are cost-effective. However, if profitability declines or where the herbicides available fail to provide adequate weed control, a weed management approach may be the only way to maintain profitability and the essential features of the chosen cropping system. The alternative of abandoning the latter may not in practice be an option, for financial or other reasons.

The role of herbicides will remain crucial, and new chemicals will continue to be required for the new weed problems that are certain to arise with further changes in agricultural practice and land and water management.

The success of the weed management approach will depend to a great extent on the resources available to weed scientists to undertake the necessary research and on the effectiveness of extension service specialists in demonstrating the advantage to farmers and others faced with weed problems. Regrettably, as pointed out by Fryer (1978) and many others, weed science is very poorly supported in most countries and this is likely to be the major constraint to further advancement. Much of the biological and ecological work needed is beyond the scope of the agrochemical industry and, moreover, there is as yet little incentive for chemical manufacturers to get involved. A further difficulty is the rigidity of some regulatory schemes, which with restrictive consumer protection legislation deters any deviation from the recommendations made by herbicide manufacturers.

In spite of these and other problems there is no doubt that weed management will play an increasingly important role in the maintenance of effective weed control practices, and hence food production in the face of rising costs of energy, chemicals, labour and machinery and diminishing land available for agriculture. While reducing dependence on chemicals, it will seldom if ever be a substitute for them. The chemical industry has therefore nothing to fear. Rather, the further development of weed management will not only allow the continued use of herbicides that otherwise would no longer be cost-effective but should open up many new opportunities for chemicals that are active not only in killing plants but in influencing their behaviour and hence their effectiveness as weeds.

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