Expert Consultation on Weed Ecology and Management

FAO, Rome
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Plant Production & Protection Division
Food and Agriculture Organization
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CONTENT

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INTRODUCTION

The importance of Weed Management in developing countries is increasing due to:

- The process of industrialization in several countries of the Third World, which makes rural labour scarce.
- Hand-weeding still occupies more than 40% of the small farmer's time in the least developed countries, in most cases carried out by women and children, and this practice does not completely prevent crop losses caused by weeds.

Some agricultural technologies currently practised in developed economies should be well validated and adapted before being transferred to the agricultural areas of developing countries.

The status of weed management in developing countries is fairly poor and needs to be improved in the near future in order to effectively contribute towards increased food production.

Weed research and extension components are lacking in many developing countries and in some countries weed research is understood as simple field herbicide testing.

There is an evident need to provide weed management technology to farmers in the developing world, but this should be based on an Integrated Pest Management approach. Such technology should include various elements, such as weed monitoring and sound criteria for the adoption of various control methods, including chemical control where required.

For this reason FAO convened the present Expert Consultation on Weed ecology and Management, which aimed at assessing the essential elements of improved weed management in the Developing World.

The objective of the meeting was to discuss how each of the elements presented by the specialists can be effectively included in future programmes for the development of weed management.

Twelve papers were presented by various weed scientists and an IPM specialist covering various issues related to improved weed management. Topics also spanned externalities providing constraints and opportunities for weed management, and current development in weed ecology to improve tools for farmer decission making.

The discussion in the last day of the meeting focused on the need to foster:

- The development of tools for invention based on ecological understanding of the dynamics of weed populations and competitive interactions between crops and weeds.
- Approaches to training farmers and extension workers.
- Development of weed management practices in the context of Integrated Pest and Crop Management.

PROGRAMME

Monday 22 September

8:30	Registration
9:00	Opening
9:30	Break
10:30	Problems related to the development of weed management in the developing world. *R. Labrada (FAO)*

Session I "Ecology"

11:00	The need for studies on weed ecology to improve weed management. *A.M. Mortimer (IRRI)*
11:30	Use of demographic models to assess potential growth of weed populations. *C. Fernández-Quintanilla (CSIC, Madrid, Spain)*
12:00	Lunch
14:00	Application of weed seed bank ecology to weed management. *F. Forcella (USDA-ARS), Morris, USA)*
14:30	Simple methods to determine weeds in the seed bank. *R. Gordon Harvey (University of Wisconsin, Madison, USA)*
15:00	Discussion
15:30	Break
16:00	Discussion

Tuesday 23 September

Session II "Economics and Management"

8:30	Practical use of weed economic thresholds. *Bärbel Gerowitt (Faculty of Agriculture, University of Göttingen, Germany)*
9:00	Basic economic criteria for Improved Weed Management. *B.A. Auld (N.S.W. Agricultural Centre, Australia)*
10:00	Break
10:30	Influence of time of weed emergence and removal yields. *M. Satin (CEBI-CNR, Padua, Italy)*
11:00	Use of simulation models in breeding competitive cultivars. *M. Kropff (Wageningen Agricultural University, The Netherlands)*
11:30	Allelopathy and its practical use for weed management. *S. Narwal (Haryana Agricultural University, India)*
12:00	Break
14:00	Basic elements for Improved Weed Management in the developing world. *I.O. Akobundu*.

15:00 Herbicide use and transgenic crops resistant to herbicides. *B. Rubin (Faculty of Agriculture, Food & Environmental Sciences, Hebrew University of Jerusalem)*

15:30 Break

16:00 IPM concepts and development. *Dr Peter Kenmore (Global IPM Facility*)
16:45 Discussion

Wednesday 24 September

Session III "Ways to improve Weed Management Components"

8:30 Discussion: Elements of Weed Ecology and Competition

10:00 Break

10:30 Discussion: Weed Management and Economics

12:00 Lunch

14:00 Discussion: Weed Management and Economics

15:30 Conclusions
Closing Remarks

PROBLEMS RELATED TO THE DEVELOPMENT OF WEED MANAGEMENT IN THE DEVELOPING WORLD

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SUMMARY

The problems posed by weeds in the developing world are briefly described and discussed. Weeds still cause severe crop losses to small farmers in developing countries and farmers' families spend a considerable amount of time weeding, which limits any further economic development. Weeding is also considered a gender issue because the most menial tasks are left mainly to the women and children, and often pregnant women are the main weeders. In addition, farmers lack knowledge on the main elements of preventing the build-up of weed seed bank in soil and its further dissemination. They are also unaware of other aspects of weed interference and the best time for weed removal.

A new approach for weed control needs to be adopted in the agriculture of developing countries. Therefore, it is necessary to initiate weed research programmes which include topics related to weed scouting methods, weed eco-biology (population dynamics, weed seed bank and others), interference (competition and allelopathy) and improved weed control practices, with major components on environmentally safe and economically feasible control methods. Weed control techniques cannot rely solely on the use of herbicides as is common in developed countries of North America and Europe.

The transfer of methodologies for such studies and resulting criteria is essential for effective improvement of weed control practices.

It is also advisable that small farmers are taught to utilize all weed management new developments in the correct way. Therefore, agricultural extension services should be strengthened in matters related to improved weed management.

I. Introduction

The world population is close to 6 billion and is expected to reach 8.5 billion by the year 2025. According to the figures provided by the recent World Food Summit (FAO, 1996), the number of undernourished in developing countries by the year 2010 will be between 700 and 800 million. The increase in population is in parallel with a decrease in cropland areas. For this reason food production in the existing crop areas must be increased in order to sustain the growing population and this can only be attained by increasing crop yields and improving cropping intensity.

Sustainable Agriculture implies food production harmonized with the protection of the environment, which means that the desired increased food production must be achieved without damaging natural resources such as air, soil, water and wild life. The use of inputs, chemicals and others, should be kept to a minimum in order to ensure this production is environmentally safe and economically feasible.

Pest control, among other agronomic activities, should be improved by minimizing the use of chemical pesticides through the rational and judicious use of different control methods that are technically effective, economically feasible to smallholders and environmentally safe. Integrated Pest Management (IPM) has developed during the last 20 years, but mainly in the areas of insect and mite control. However, weed management still relies mainly on the use of herbicides in developed economies while hand-weeding is the main control method in the developing world.

In fact, it is of the utmost importance to improve weed control measures in developing countries as one of the ways to increase crop production and to create better working and living conditions for farmers and their families.

The scope of the present paper is to briefly describe the problem of weed control in the developing world and the need for its improvement based on new technical approaches.

II. Weeds and associated problems

2.1 Socio-economic problems

It is well known that weeds compete strongly with crops for light, water and nutrients; weeds also exudate or leach substances from roots and leaves, respectively, which are toxic to crops. This brings about severe interference with normal crop growth, causing high crop losses and reducing the quality of produce.

In the developing world, as already stated, the main weed control method of smallholders is either hand-weeding or hoe-weeding; more that 50% of smallholders' labour is devoted to weeding (Labrada, 1992), which is time-consuming and limits the area that can be cropped successfully (Sauerborn and Kroschel, 1996).

Weeding may also be considered a gender issue because the menial tasks are carried out mainly by women and children, and often pregnant women are the main weeders.

Some twenty years ago, smallholders based their crop production on long-term fallow and shifting cultivation (Sauerborn and Kroschel, 1996). Thus they were able to avoid severe weed problems and degradation of soils after a certain period of cropping. These practices are no longer feasible due to the high demand for food, increased population and reduced availability of cropland.

2.2. Farmers' lack of knowledge on weeds

Smallholders are well acquainted with their plots and successive cropping gave them further knowledge of the usefulness of various practices. They normally identify weeds by their local common names and have some idea of their behaviour.

However, they have neither knowledge of the real problems caused by weeds nor the awareness of several bioecological features of weeds, their level of reproduction and dissemination. An example of this is the case of the root parasitic weeds *Striga* spp. (in Africa South of Sahara) and *Orobanche* spp. In North Africa and the Near East, in most cases farmers do not know that these weeds have two phases (one subterranean and one aerial) and that the most damage is caused by the root parasitic weed during the first phase. They are also unaware these weeds can be controlled in the long term by reducing weed seed bank in the soil and also by avoiding seed setting by the weeds. Therefore training of farmers on aspects related to weed biology may help them to improve parasitic weed control practices.

Farmers often weed at the wrong crop stage and do not understand that weed control is much more important during the so-called critical periods of competition to avoid significant crop losses. It is for this reason that elements of weed ecobiology and interference should also be part of any farmer-training programme on weed control.

2.3 Limited weed control technologies

Low resource smallholders control weeds by hand-pulling or hoe-weeding. Human energy spent on weeding prevents increased farmer productivity and even any possible intellectual self-development. Other control methods are used in a limited scale.

Several specialists involved in agricultural issues from different part of the world accept the fact that hand-weeding is unavoidable. Some consider that the replacement of this practice may cause more problems of unemployment in least developed countries, while others believe that weeding is a secondary issue and it is the lot of farmers in the developing world to continue to carry out such menial tasks for the rest of their lives.

III. Possible alternatives for improved weed management

3.1 The approach

As mentioned above, the arsenal of weed control measures of small holders in developing countries is very limited.

It would also be completely wrong to import weed technologies that are not fully applicable to smallholder agriculture in the tropics and sub-tropics (Akobundu, 1996).

New weed control technologies should be attractive to small farmers. On the one hand they should serve to reduce weed stand and increase crop yields and on the other, as Akobundu (1996) states, any intervention should not have fatal consequences of possible interference with the ecological balance or provoke any problem to human health. One can assume that the technologies to be developed should have a strong component of use of cover crops, crop rotation, intercropping and, whenever possible, use of organic manure. Possibly most of the measures needed to restore soil fertility may form a major part of new weed control measures introduced. Economically and environmentally effective cropping systems adopted by farmers are the key to successful weed management. The latter should be understood as a major component in any crop management system.

Control efforts should also be concentrated on key weed species which are normally widespread and abundant in particular ecologies. Therefore there is a need to initiate and develop a relevant weed research programme, which should consist of studies of weed population behaviour and also take into consideration the socio-economic aspects of smallholders.

In all cases it would be completely wrong to assume that technologies effectively implemented in developed countries may also function well in developing ones.

3.2 Weed Research

A survey on the status of weed management in developing countries carried out by FAO (Labrada, 1986) revealed that only 25% of 80 countries surveyed have an acceptable level of weed research, but in many of these programmes studies are mainly devoted to the adaptation of foreign weed control technologies and/or herbicide application.

Only a few of these programmes have included aspects of weed ecobiology and other criteria for the implementation of weed control measures.

Studies of weed ecology and population dynamics are very scarce in the tropics and sub-tropics; the same applies to the **behaviour of weed seed bank**. It is important for weed scientists to keep in mind that the key issue for improvement of weed management in developing countries is an understanding of the abiotic and biotic conditions responsible for the behaviour and evolution of weed flora in the tropics and sub-tropics.

Studies on the **biology of several tropical weeds** have been carried out by various weed scientists from developing countries, but many of them have not been carried out in the right environment.

Little has been done regarding **regular monitoring of weed infestation and possible crop losses**. In many countries of the developing world sound **weed scouting systems** are unknown and it is not possible to predict weed stand in coming crops.

Many authors have studied **critical periods of weed competition** in several crops, but available data need to be systematized.

A vague idea of **allelopathy** phenomena exists in many developing countries and in some others this problem is completely unknown. Very little has been done concerning the use of allelopathic crops for weed control.

Economics of weed control in small farming systems receive very little attention and this is an essential issue to be taken into consideration. There are several economic criteria related to weed control in whole farm that, if taken into account, may have a great impact on the economy of small farmers.

All these issues, and others, need to be researched and considered as basic criteria for the further development of weed management technologies.

Although developed economies still rely too heavily on chemical weed control, it is also true that in this part of the world studies of weed ecobiology, interference and economics have been successfully developed. Therefore the transfer of methodologies for such studies and resulting criteria can be used to effectively improve weed control practices in the agriculture of developing countries. This knowledge could possibly be transferred through the publication and dissemination of general guidelines on weed research and training on these aspects.

To conclude this section, weeds are a compounded problem; cost-effective and environmentally safe weed management requires basic knowledge of weed eco-biology and an understanding of socio-economic factors influencing acceptance and sustainability.

Major elements to be included in a weed research programme are as follows:

- monitoring of prevailing weed species and their abundance,
- weed eco-biology, including population dynamics and seed bank behaviour,
- weed interference, including competition and allelopathy, and
- improvement of weed control measures, taking into consideration their influence on weed composition and the environment.

Terry (1996) rightly states that in weed management there are pitfalls to be avoided and lessons to be learnt from the industrialised countries. In the opinion of this author, elements of weed ecobiology, interference and economics experienced in developed economies are those which need to be learnt by weed scientists in developing countries.

3.3 Transfer of technology

Any research results should be effectively and quickly transferred to farmers. For this reason the elements of weed research studies should be as practical as possible. For example, nowadays modelling is an everyday tool for predicting losses and/or behaviour of pest organisms. However the feasibility of its application in the developing world would be very limited because of the lack of appropriate equipment and infrastructure. The same may be applicable to the so-called economic weed thresholds.

In the case of weed control technologies, it is necessary to keep in mind that the application of sophisticated technologies currently used in Europe and North America is not feasible in the low resource small farmers' systems prevailing in the developing world. In addition, any new weed control technique should be tested beforehand and its acceptance by farmers evaluated.

Small farmers must be taught to utilize all new developments on weed management in a proper manner. For this reason agricultural extension services should also be strengthened in matters related to improved weed management.

Finally, weed control techniques cannot rely solely on the use of herbicides and integrated weed management, with a major component on cultural and physical practices, should be the way to effectively reduce weed stands with minimal risk to the environment and human health in the agriculture of developing countries.

The present consultation on **Weed Ecology and Management** has been convened by FAO to assess the essential elements for improved weed management in the developing world, to discuss all these issues and consolidate sound recommendations for future programmes on weed management in the developing world.

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ECOLOGY

THE NEED FOR STUDIES ON WEED ECOLOGY TO IMPROVE WEED MANAGEMENT

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SUMMARY

Weeds are often the principal biotic constraint to crop production in developing countries and the pressing need to increase food production presents an immediate challenge for weed scientists. Of equal importance is the need to protect the environment to ensure sustainable agriculture. This requires critical appraisal of the impacts of individual weed control tactics in the development of integrated weed management procedures, considering economic, ecological and sociological consequences of their use. This paper discusses the conceptual background to this approach from an ecological perspective. It is argued that participatory ecological research in collaboration with farmers on weeds is an essential component in the development of sustainable weed management.

I. INTRODUCTION

In 1979 in the first volume of a new journal entitled Protection Ecology, Geier and Clark discussed the nature of pest control and asked the question ' how should its future be viewed - as production process or applied ecology ' ? Undoubtedly pest control is a process in the sense that it has as a product, elevated plant yield through crop protection. However what is at issue is the manner in which that product is achieved given that all agro-ecosystems *(sensu* Smith and Van den Bosch, 1967) are a consequence of the imposition of a production system, (*viz.* agriculture), and are not a consequence of ecological design (*sensu* Garden of Eden, or *Jannatun naim).* Eighteen years later, Blacklow (1997) reviewing the same topic from the view of 'sustainable weed management' concluded that the appropriateness of particular technologies for weed control must be assessed by society with legitimate concerns over the quality of the environment (both internal and external to the agro-ecosystem) and over the use of resources for weed control. At the heart of the argument in both papers is the manner in which the fundamental conflict of increasing food production for human consumption and protection of the local, and increasingly global, environment is resolved. Moreover, Richards (1985) argues against acceptance of the assumption that transference of 'high-input advanced' solutions will be the solution to weed problems of low-input farming systems of lesser developed countries. The continuing losses due to weeds inequitably distributed across countries and agro-ecosystems (Labrada, 1996), the evolution of herbicide resistance (Gressel and Baltazar, 1996), shifts in the weed flora in response to weed management (Ho, 1991), the chemical contamination of water sources (Sieber, 1987) and soil erosion through excessive cultivation (Garrity, 1993) all attest to the need to develop systems of weed management, that are sustainable. Such sustainability will arise through the development of integrated weed management systems.

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It is with this background in mind that this paper discusses the need for ecological studies for improved weed management, focusing on developing countries. Specific approaches and methodologies are not dealt here as they are addressed by other authors in these proceedings. The phrase 'weed management' is favoured over 'weed control' because the latter implies a dominance that is, in many instances, illusory.

II. The Concept of Integrated Weed Management (IWM)

IWM is often thought of as the application of numerous alternative technologies to reduce weed abundance, including cultural, genetic, mechanical, biological and chemical means (Regnier and Janke, 1990). However in a formative definition, Buchanan (1976) argued that IWM involved ' the deliberate selection, integration and implementation of effective weed control measures *with due consideration of economic, ecological and sociological consequences* '. Implicit then, in this original definition is the suggestion that there is the need for assessment of the wider impacts of weed management technologies over and above the goal of reduction of weed biomass itself. Part of the design of integrated weed management procedures therefore should be an environmental impact analysis (Table 1) of each of the component practices (Table 2) themselves. Inherent to such an analysis, however, will be the need to make a value-judgement on the relative risks and benefits of each component as discussed below.

Table 1. Questions in an environmental impact analysis of components of an integrated weed management program. In analysis it is necessary to question the "worth" of utilising each component (see Table 2). Questions are not ranked in importance.

Does the component

- arrest the development of weed abundance so that weed interference with crop yield is below some acceptable (economic injury) level in the field ?
- prohibit succession / species substitution in the composition of the weed flora in the field ?
- prevent change in genetic structure of species populations within the weed community that will prohibit existing control measures ?
- achieve management of weed abundance in an environmentally acceptable manner, for example minimising residues, conserving soil and sustaining biodiversity in the agro-ecosystem ?
- 'fit' in terms of economics and practicality at the whole farm level and with other integrated pest management practices ? and
- represent a socially acceptable practice that is appropriate to 'end-user' communities and is therefore adoptable / adopted ?

Table 1 may be thought of as an academic abstraction of little relevance to the farmer but it serves to provide both a checklist for policy makers in evaluating the impact of existing and new technologies and as a framework for developing research directions.

In ensuring that ecological research for weed control has maximum impact, it is imperative to understand the socio-economic context of the farming system (Chambers *et al*, 1989, Scoones and Thompson, 1994). This is especially true for tropical farming systems which involve multi-storey cropping, intercropping, crop rotations and long term fallowing. Externalities in the form of cultural and socio-economic norms will govern the acceptance of a new technology or promotion of the continued use of existing ones. For example, farmers in the rainfed lowlands of the Philippines alternating rice in the wet season with vegetables in the dry still do not count the opportunity cost of manual weeding in vegetables and may continue to practice family weeding; similarly the drudgery of manual weeding, predominantly by women, in Africa is considered a norm (Akobundo, 1996), albeit undesirable by many standards. Additionally, the question of what plants are 'weeds' needs to be carefully considered (Price, 1997).

Whilst understanding farmer approaches and constraints in weed management at the macro (farming system) level, the 'ecological theatre' in which weeds cause damage is the farmer's field and the major source of damage, (yield loss), occurs because of competition for limiting resources at key stages in the life of the crop. (Note however there are other sources of damage which may need to be considered in the wider perspective, Auld *et al*, 1987; Mortimer, 1990).

Table 2 Components of weed management at the field level that may be integrated together into a suite of measures. The list is illustrative and not exhaustive.

Crop husbandry	**Management interventions**
Seed bed preparation	Mulching
Crop establishment method	Land cultivation
Competitive cultivar	Manual weeding
Inter cropping	Directed weeding
Seeding rate	Chemical weeding
Purity of crop seed	Biological control
Water management	Timing and frequency of intervention
Fertiliser management	
Crop rotation	
Crop diversity	

The first three questions in Table 1 relate to limiting this damage in a sustainable way at the field level because there is no change in the weed flora (either shifts in the weed flora or evolution of herbicide resistance) and there is cost-effective weed control. The fourth is a validation that the weed control practices are acceptable in that they have no indirect effects that are perceived to be disadvantageous to consumers of farm products or to the environment used in production. I use the word 'perceived' judiciously because validation involves value judgement in social and economic contexts, relating for instance to production levels (Pingali *et al*, 1997), relative profitability (Pandey and Pingali, 1996), cost effectiveness (Ampong Nyarko and De Datta, 1991), environmental acceptability (Hill *et al*, 1997) and international trade implications (Cullen, 1993). One manifestation of the different degrees of acceptability are the introduction of minimum residue levels (in food) as trade barriers and the preferential consumption of 'pesticide free' foods (Williams, 1992). Another is the belated recognition of the need to maintain a diverse agricultural landscape in which the bio-diversity of the non-crop habitat is a biological resource for predators for insect pest management (Kenmore, 1996), as well as for ethical reasons. A third, in the developing world, is that particular technologies are prone to risk of misuse because of insufficient knowledge of farmers and lack of access to correct information sources and equipment. An obvious example in intensive arable farming is in the use of chemical inputs (nutrients, pesticides) that occur or result in residues in surface and ground waters (Crosby, 1996) and may lead to ecosystem damage in particular to aquatic food chains but also to human health (Pingali and Marquez, 1996).

Farmer options for weed management are potentially diverse and highly interactive in effect and may be classified under two headings, crop husbandry and intervention (Table 2). Crop husbandry is defined here as all of the practices pursued to 'raise a healthy crop' or alternatively to minimise the yield gap (Teng, 1990) - assuming the absence of weeds. It is these practices that define the habitat template which interspecifically selects species into the weed flora (Mortimer 1994). For example in irrigated rice, time, depth and duration of flooding is a critical determinant of establishment success of grassy weeds (Smith and Fox, 1973; Pane and Mashor, 1996).

A desirable working maxim in developing IWM must be to attempt to minimise the number of interventions *per se* and where interventions are necessary to minimise negative environmental impacts. Externalities (for example, access to equipment) will provide constraints and it is of course here where value judgements as to what is 'acceptable' comes in to play. However to follow such a maxim it is necessary to achieve two conditions.

The first is to ensure that there is a paradigm shift in the research topics considered as 'weed science' in research institutions and universities. This involves switching the research focus from comparative study of individual intervention events (for example new herbicides) to ecological and systems analysis at weed species, weed community and agro-ecosystem level (Kropff and van Laar, 1993; Swanton and Weise, 1991). Recent textbooks reflect this way of thinking (Cousens and Mortimer, 1995; Radosovich *et al*, 1997).

The second is to develop, in collaboration with farmers, sustainable integrated weed management systems that ensure high yields, optimised for inputs, and expose the fallacy of 'silver bullet' solutions. In essence, development and application will be a recursive process in which the indigenous knowledge and experience of farmers is an essential resource because integrated weed management is a knowledge intensive process. As others have remarked, it will take the combined resources of influential and experienced farmers, members of NARS and NGOs, scientific researchers in academia and government institutions, extension officers and private sector representatives to develop IWM programmes and to transfer the technologies leading to adoption (Ho, 1996).

III. ECOLOGICAL RESEARCH BY WEED SCIENTISTS FOR FARMERS

Ecological studies of weeds and weed management may be conducted with a diversity of objectives in mind - for instance a) autecological comparison of weed species ; b) ranking competitive outcomes amongst species and yield loss assessment; c) measuring the impact of new technologies on the dynamics (change in abundance) of 'hard-to-kill' species; d) quantifying weed community structure and analysing its causes; e) assessing invasiveness at field, regional and geographical scales; and f) measuring the impacts of components of IWM, for instance on non-target organisms, on soil conservation, and on human health. Whilst all such studies will contribute useful knowledge to weed management, prioritising research for the most impact in developing countries is an important question ? To contribute to debate towards an answer, four points can be made.

1) Lotz *et al* (1990) point out that not all non-crop species in a field are damaging and that within a crop there will be non-competitive biomass. For most weeds there is insufficient information to be able to quantitatively rank their mean damage potential and the variability that arises from sources of inter-seasonal variation. Both empirical and mechanistic models are now available for these measurements (e.g. Cousens, 1985; Sattin *et al*, 1992, Kropff and Van Laar, 1993). It is of considerable importance to match this knowledge with farmer perception of 'injury levels' and practice in managing weeds. The question as to whether or not economic thresholds will be used in decision making for weed management in developing countries is a moot point and it may be that decisions stem from action thresholds triggered largely on the experience of the previous season's weed problems (Moody, 1988). Cousens (1987) cogently discusses threshold concepts and critically examines their value. An outstanding and urgent area of weed research is in helping plant breeders to produce competitive crop cultivars and this will probably only come through an understanding of the dynamics of plant competition through eco-physiological approaches (Kropff and Bastiaans, 1997).

2) We need to be able to identify and recognise the biological and ecological factors leading to the long term persistence of species in weed communities, placing emphasis on temporal and spatial variation at the field level (Mortimer *et al*, 1997a). Since the persistence of most weed species is contingent upon the presence of a buried seed bank, knowledge of its size and the flux of seeds within it, in relation to land cultivation practices, is essential (Forcella and Burnside, 1993). Such information together with the depth from which weeds can emerge, underlies the design of stale seed bed techniques, which offer opportunities for tropical weed control (Mortimer *et al*, 1997b). Crop rotation and season long fallowing are perhaps the most significant sources of temporal variation in the habitat of weeds and most powerful determinants of weed abundance, as the early history of agriculture illustrates. Equally important also, is an understanding of the agronomic factors, especially tillage and harvesting practices, that ensure spatial variation in habitat conditions at the field level leading to patchiness of weeds.

3) The value and limitations of studies of the population dynamics of individual weed species needs to be fully appraised. Population growth rate is a useful parameter to indicate the change in weed abundance that may result from change in weed management as it incorporates all of the phases in the life cycle of a weed in which regulation can occur and also the phenotypic plasticity in reproduction that is so commonly observed in weeds. However predictions of change (by sensitivity analysis) using empirical models will have low precision and be only qualitative, whereas mechanistic models taking into account driving variables will clearly improve precision. Nevertheless, qualitative predictions will be of considerable value if they are used to identify the key management factors that have the greatest effect in tending, on average, to achieve negative population growth rates (Cousens and Mortimer, 1995).

4) Modern multivariate techniques (Ter Braak and Prentice, 1988) offer considerable potential to quickly identify the relative importance of weed management factors in determining weed community structure. When applied to experimentally manipulated weed communities, they provide a first step towards predicting the potential for changes in the weed community in response to management.

IV. ECOLOGICAL RESEARCH IN COLLABORATION WITH FARMERS

Critical responses to, and non-acceptance of, 'top-down' advice on pest management from extension workers by farmers is well known, (Millar, 1994). Such observations strongly suggest that transferring the results of ecological research embodied within integrated weed management practices to farmers will involve more than just demonstration plots. There will be a need to illustrate, to both extension workers and farmers, the *application* of ecological knowledge. Strategic extension campaigns (Adhikarya, 1994) and farmer field schools (Kenmore, 1996) in insect pest management illustrate the importance and success of the farmer participatory orientated approach in this regard. This represents a new challenge to weed researchers and will, from the beginning, involve farmer participatory ecological research. In the first instance and for example, simple field experiments will need to be set up (as a consequence of facilitated discussion and debate) to indicate the sources of weeds (soil or crop seed), the differing competitive 'strengths' of weeds, and the effects of plastic responses of weeds escaping management practices. Farmer's innovations in weed management have been chronicled by a number of investigators (Chambers *et al.* 1989) and Moody (1994) cites a range of examples where farm experimentation has lead to improvements of, and adaptations to, technology, independently and latterly confirmed by research. It is therefore to be expected that dialog will be highly fruitful and lead to deeper understanding on both sides.

Acknowledgements
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APPLICATION OF WEED SEED BANK ECOLOGY TO WEED MANAGEMENT

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SUMMARY

Knowledge of weed seed bank ecology has direct management applications. Although seed banks are notoriously difficult to analyze with high levels of statistical accuracy, such accuracy may be unnecessary for applying seed bank information to management decisions. Consequently, seed banks of many arable fields may be sampled adequately with far less time, effort, and expense than originally assumed.

Dormancy of seed bank constituents also is important for management decisions. Dormancy is species-specific and regulated by complex phenomena, but some progress has been made recently in predicting dormancy relief and induction in field settings. Even more progress has been made in forecasting seedling and shoot emergence, which is perhaps the single most critical type of ecological information necessary for efficient and effective weed management. However, much additional research will be necessary, especially for tropical weed species, to fully apply the emerging principles of seed bank ecology to weed management.

I. INTRODUCTION

Weed seed banks provide weed managers with foresight of considerable potential. However, the acuity provided by this information depends greatly on the level of ecological knowledge of weeds possessed by the manager. Although perfect vision is impossible, ecological knowledge serves as a lens that helps the manager better focus on the spectrum of management practices available. The purpose of this report is to describe the types and boundaries of ecological information and knowledge required by the manager to make decisions that are appropriate agronomically and economically. These topics include seed bank sampling, emergence potential, and emergence timing.

II. SEED BANK SAMPLING

The number of viable seeds in a seed bank, identified to species, is especially useful data for weed managers. Viable seed bank densities establish the potential infestation level of an arable field. Even though the full potential infestation level might not be realized in any given year, the utility of this type of information has been documented for weed management in grain crops such as maize and soybean (Forcella et al. 1996b).

Unfortunately, collection of seed bank data is time consuming and expensive. High costs reflect three aspects of data collection. First, large numbers of samples (e.g., soil cores) must be taken from each field for reliable estimates of seed bank densities. Several research teams have determined that at least 100 soil cores must be collected and processed in order to have 95% confidence in the resulting data (Goyeau and Fablet 1982, Barralis et al. 1986, Benoit et al. 1989, Zanin et al. 1989, Dessaint et al. 1992). Second, even with modern equipment, such as elutriators (Wiles et al. 1996), and centrifuges (Buhler and Maxwell 1993), isolation of seeds from soil is a tedious and expensive process. Lastly, until automated image analyzers are improved (Buhler and Maxwell 1993), the human eye will remain the best tool for identifying seeds to the species level. Indeed, this latter process may be the most limiting step for all aspects of seed bank sampling in terms of time and money (Wiles et al. 1996).

The "seedling emergence" method of seed bank analysis avoids the problems of seed-soil separation and seed identification inherent to the "seed extraction" method. In this method multiple soil cores from a field may be aggregated, thoroughly mixed, spread as a 2 to 5 cm deep layer of soil onto a single tray, and stored in conditions that promote germination. Emerged seedlings are counted by species after 2 or 3 weeks. After counting seedlings, soil in the trays is dried, thoroughly remixed, and the cycle is repeated. For weeds of arable soils, 2 or 3 cycles is often sufficient to estimate seed banks (Forcella 1993). Thus, at least 4 weeks are required to process samples using the seedling emergence method. If done properly, the method allows timely projections of subsequent weed populations (Forcella 1992).

Despite the drawbacks of any seed bank sampling method, there is some room for optimism with the use of seed bank data for weed management purposes. This optimism arises because the need for accuracy in seed bank estimation may not be as high as initially assumed. Most analyses of seed bank sampling protocols implicitly assume that a 95% statistical confidence level is necessary (Goyeau and Fablet 1982, Barralis et al. 1986, Benoit et al. 1989, Zanin et al. 1989, Dessaint et al. 1992). Although this assumption may well be valid, it probably is based more on statistical tradition than on relevance to weed management. Naturally, high levels of precision and accuracy are important when determining seed bank densities for some purposes; e.g., multi-year demographic forecasts. However, knowledge of whether an *Amaranthus* seed bank contains 950 or 1000 seeds m^{-2} may not be important for making a weed management decision. Whether the seed bank contains 95 or 1000 seeds m^{-2} is probably of much greater importance. In other words, seed bank density differences in terms of "orders of magnitude" (1, 10, 100, 1000, etc.) are likely to be more important for management decisions than differences that are distinguished with 95% confidence limits. These points can be illustrated with a weed management decision aid such as *WeedSim* (Swinton and King 1994).

WeedSim is a decision aid that uses seed bank densities, in conjunction with other weed biology parameters, to determine the weed management strategy that maximizes profit for the farmer after taking into account such variables as expected crop yield, commodity price, management costs, weed-crop competition, and so forth. We can insert different seed bank densities into this software program and observe the sensitivity of the recommendations to varying densities. Figure 1 illustrates the types and costs of management recommendations that would maximize profit for a maize crop given varying densities of seeds in a seed bank composed of *Setaria faberi*. First, note that the x-axis (seed bank density) in this figure is on a logarithmic scale. Second, observe that *WeedSim* recommendations change only five times as seed bank density varies across five orders of magnitude, from 1 to 100,000 seeds m^{-2}. This information indicates that weed management practices are, in fact, sensitive to changes in seed bank densities, but not highly sensitive. It also suggests that seed bank sampling schemes that aim toward 95% statistical confidence are far more accurate than what is actually necessary for the sole purpose of making weed management decisions.

If high levels of accuracy and precision are unnecessary for making weed management decisions, then how many soil cores should be taken to adequately sample a field? Some of the many excellent publications that emphasized 95% statistical confidence (Goyeau and Fablet 1982, Barralis *et al.* 1986, Benoit *et al.* 1989, Zanin et al. 1989, Dessaint *et al*. 1992) help solve this problem. For example, using the coefficients and equations reported by Zanin *et al.* (1989; Figure 1, November samples), and assuming a mean of 5 seeds per soil core and a good precision level of 20%, then the sampling intensities necessary to determine seed bank density would be 6, 15, 34, 57, and 80 soil cores per field if statistical confidence levels are set at 40, 60, 80, 90, and 95%, respectively. The 95% confidence level requires too many samples for busy farmers or crop consultants to take and process. On the other hand, sampling intensities associated with 60% and 80% confidence levels (15 and 34 cores per field) are far more practical for seed bank analyses devoted to weed management rather than weed research.

Another, and far simpler, approach to this problem is plotting sample variance against sample number as the number of soil cores increases from 3 to larger values. Sample variance will be high and unstable with low sample numbers. As sample numbers increase variance eventually will decrease and stabilize. At the point of variance stabilization, any increase in sample number will provide little additional information regarding the density of seeds in the seed bank. Sample variances stabilize at 10 to 15 soil cores for individual research plots over a range of sizes and locations (Forcella et al. 1992). For actual farmers' fields sample variances stabilize at about 20 to 40 cores for common weed species, such as *Setaria viridis* and *Amaranthus retroflexus* (Figure 2). Although accuracy inevitably will increase as sample numbers rise, little additional information about seed densities accrues beyond 20 to 40 soil cores per field.

Assuming that seed bank densities can be determined with sufficient accuracy, the value of this information still is limited. The limitation arises for two reasons. First, seeds in soil exist in various states of dormancy at any point in time. Thus, even high-density seed banks may result in only sparse seedling populations if most of the seeds are dormant. Conversely, low-density seed banks may give rise to relatively dense seedling populations if most seeds are not dormant. Second, when seeds have the ability to germinate, they do so over extended time periods. This means that the timing of seed bank sampling and subsequent seedling population assessment must be coordinated temporally. Simply stated, seed banks must be sampled before seedlings emerge. Surprisingly, this logical credo was forsaken in many seed bank studies reported in the literature.

Thus, two important aspects of weed biology must be considered to make full use of seed bank density information. I refer to these issues as emergence potential and emergence timing, and they will be described in the following sections.

III. EMERGENCE POTENTIAL

Seeds of many summer annual weeds are dormant when they are shed from their parental plants. Even older seeds in the seed bank may be in a state of dormancy at the end of summer. Sometime during the following autumn, winter, and/or early spring a proportion of these seeds becomes capable of germination. At this time they have maximum "emergence potential." Maximum emergence potentials of several species were reported by Forcella et al. (1997). Examples include *Setaria faberi* 100%, *Abutilon theophrasti* 54%, *Polygonum pensylvanicum* 49%, *S. viridis* 21%, *Amaranthus* spp. 13%, *Chenopodium album* 10%, and *P. convolvulus* 5%.

Maximum emergence potential, however, is rarely realized by these species. Certain environmental conditions may occur in spring or early summer that induce what is known as "secondary dormancy" in some of these species. We do not yet know the conditions that induce secondary dormancy in most species susceptible to secondary dormancy. However, we have been able to estimate these conditions for some species based upon empirical relationships between the proportion of a seed bank that emerged over the course of an entire growing season and single-day events that occurred in spring or early summer (Forcella et al. 1997). Departures from maximum emergence potential can be predicted for some species based on daily weather events through the use of computer software known as *WeedCast* (Reese and Forcella 1997, Forcella 1998). Similar predictions for most other species await greater and more detailed research efforts.

Real-time information concerning the level of dormancy in weed seed banks arms producers and crop consultants with valuable knowledge (Forcella et al. 1996a). Such knowledge permits more rational decisions to be made regarding the necessity, degree, and type of weed management. For example, assume that a seed bank contains 2000 seeds m^{-2} of *S. faberi* and that corn will be the crop. The level of dormancy within that seed bank will determine the subsequent degree of weed infestation, potential crop yield loss, and the type of weed control necessary to reduce that infestation to a level that affects little yield loss.

We can examine the effects of induction of secondary dormancy in the *S. faberi* seed bank on expected weed densities, potential corn yields, variable control strategies, and financial returns through combinations of *WeedCast* predictions and *WeedSim* (Swinton & King 1994) recommendations. If dormancy is induced at either of three different times, say April 19, May 9, and May 18, then emergence potential would be 20, 50, and 80%, respectively (Forcella et al. 1997). Thus, the maximum potential number of seedlings arising from a seed bank of 2000 seeds would be 400, 1000, and 1600 seedlings m^{-2} of *S. faberi* for these three levels of emergence potential. Supplying these three seedling densities independently to the *WeedSim* management decision aid, the resulting management recommendations are (1) no control, (2) rotary hoe, and (3) soil-applied atrazine, respectively (each in conjunction with interrow cultivation, which is assumed by the *WeedSim* model). Thus, as induction of secondary dormancy is delayed, weed densities increase, and weed management intensifies accordingly.

Complicated, but more realistic, scenarios also can be examined. For example, assume induction of secondary dormancy for species such as *P. pensylvanicum* and *S. faberi* occurred early (April 6) for a prospective soybean field. If the total seed bank was 2000 seeds (1000 seeds of each species), the resulting densities in soil that was moldboard plowed, which buries many seeds too deep to germinate (Forcella et al. 1996a), would be 33 *P. pensylvanicum* and 87 *S. faberi* seedlings m^{-2}. Only rotary hoeing would be recommended by *WeedSim* to control this level of infestation. However, if *P. pensylvanicum* dormancy again was induced on April 6, but induction of *S. faberi* dormancy was delayed until May 10, then 33 *P. pensylvanicum* and 434 *S. faberi* seedlings m^{-2} would be expected to emerge, which would elicit a *WeedSim* recommendation of rotary hoeing followed by an expensive postemergence application of sethoxydim. Clearly, knowledge of the effects of weather on induction of secondary dormancy allows farm managers to make more informed decisions, in real time, regarding weed management.

IV. EMERGENCE TIMING

The time at which weed seedlings emerge is, perhaps, the most critical aspect of the ecology and management of weed seed banks. Powerful management tools such as herbicides are even categorized according to when weeds emerge (i.e., pre-emergence and post-emergence). For this reason knowledge of weed emergence patterns and microclimate effects on seedling emergence would be expected to be at a high level of sophistication. Surprisingly, and unfortunately, this expectation is in error. Only relatively recently have serious attempts been made to develop predictive tools based on an understanding of weed seed and seedling responses to microclimate in field settings.

Mechanistic seedling emergence models that are sensitive to temperature, soil water potential, or other factors are rare. Vleeshouwers (1997) provides a good review of existing models. Although these models have had some success, they have not been adopted widely by crop advisors, farmers, or even other scientists. There are a number of likely reasons for lack of adoption by potential users, but two that are at the forefront are site-specificity and user-friendliness of the models. In other words, most current models work only in local situations and they are difficult to use by anyone other than the individuals who developed them.

To facilitate the use of research-based emergence predictions, the *WeedCast* software program (Reese and Forcella 1997, Forcella 1998) was adapted to incorporate two basic sets of equations for each of several species of summer annual weeds. The first set of equations describes the empirical relationships between emergence of weeds and cumulative soil growing degree days (GDD) when soil moisture is high. Soil GDD is the average daily soil temperature at 5 cm depth less 4.4 C. The second set of equations essentially tells the first set to equate the daily soil GDD value to 0 on any day when soil moisture falls below a threshold level that is characteristic for each species.

The equations used by *WeedCast* were derived from soil temperature, estimated soil moisture, and timing of seedling emergence data that were collected in two separate studies. The first study involved 13 species over the course of five years at the Weed Nursery of the University of Minnesota's Rosemount Experiment Station. The second study also involved 13 species, and it was conducted by members of the NC-202 Regional Research Committee. These latter data came from 10 site-years from Ohio to Colorado, and Missouri to Minnesota (Forcella 1998, Forcella et al. 1998). From all of these data "emergence curves" were constructed; i.e. cumulative relative seedling emergence plotted against cumulative soil GDD. These data were fit to Gompertz equations, but best fit equations were not used. The Gompertz equations used by *WeedCast* are "upper limit" equations. That is, they represent the emergence of each weed species as if soil moisture never limited emergence. In reality, however, soil moisture often limits seedling emergence. The manner by which *WeedCast* accounts for the effects of soil moisture is described in the following paragraph.

At all of the same sites and during the same years that emergence data were collected , soil moisture (MPa) at 5 cm was estimated daily. These daily values could then be visually inspected to determine threshold values for inhibition of seedling emergence. These soil moisture thresholds and GDD (Gompertz) equations were then combined. In essence, *WeedCast* estimates soil moisture values each day, and when these daily values fall below the threshold value for the weed species of interest, then GDD are not accumulated. Accumulation of GDD does not resume until the next significant rainfall. Consequently, seedling emergence ceases during dry spells and increases only when soil moisture is above the designated MPa threshold.

Equations used by *WeedCast* were tested using site-specific daily soil temperature and rainfall data. Results from preliminary models were then compared to observed emergence curves. When good relationships were found, these empirically derived equations were then inserted into the *WeedCast* software.

Applications of forecasts of weed emergence timing are many and varied, and only a few examples will be described in this and the following paragraphs. Example 1: Non-residual forms of preplant weed control may be highly effective. These forms of control typically involve seedbed preparation, which can include the use of burndown herbicides in no-till systems or disking and harrowing in plowed soils. Early seedbed preparation typically enhances soil-seed contact for both the weeds and the crop, and it often results in high levels of weed presure. However, delayed seedbed preparation through disking and/or harrowing can be quite effective for weed control (Gunsolus 1990), but simultaneously lead to low crop yields because of late planting. The question is one of optimization; that is, at what point during the sowing season might the seedbed be prepared to elicit simultaneous maximization of crop yield and minimization of weed density (Forcella et al. 1993). Half of this problem may be solved by investiagtions of the degree of control achieved through seedbed preparation at varying levels of predicted weed emergence. For example, a near-linear relationship exists between the control of *C. album* and the predicted emergence percentage at the time of mechanical seedbed preparation for soybean (Figure 3). In this example no other form of weed control was used, except for a single interrow cultivation. Similar relationships have been shown for other species (Forcella et al. 1993).

Example 2: Once a crop is sown “soil-applied” weed management practices may still be used, such as applications of preemergence herbicides. Use of rotary hoes and harrows also may be considered forms of soil-applied weed management. A problem often confronted by producers in humid regions is rainfall immediately after crop sowing. Wet soils may prohibit vehicle traffic and, therefore, the application of preemergence herbicides. After soils dry adequately to support vehicles, the question arises regarding the timeliness of a preemergence herbicide. Is it too late, or have weeds remained sufficiently quiescent to permit application of such a chemical? An understanding of predicted emergence percentages and preemergence herbicide efficacy can answer this question. For example, good control of *S. viridis* in soybean can be affected any time up to 5% predicted emergence with a “preemergence” application of metolachlor. Similarly, *A. retroflexus* control is effective if metribuzin is applied up to 20% predicted emergence (Figure 4).

Example 3: An analogous problem is that of the timing of mechanical weed control, such as rotary howing and interrow cultivation. A rule-of-thumb in row crops, for example, is to rotary hoe between 7 and 14 days after sowing. Use of this guide, however, results in very inconsistent levels of control. We have found more consistent and predictable control when mechanical operations are implemented at specific levels of weed emergence rather than days after sowing (Oriade & Forcella 1997). For best control of *Setaria* spp., rotary hoes and interrow cultivators should be used at the time of 30% and 60% predicted *Setaria* emergence, respectively (Figure 5).

SUMMARY AND CONCLUSIONS

Measurements of seed bank densities and forecasts of weed seed dormancy and weed seedling emergence are possible despite the many possible and actual errors encountered with such estimates and predictions. Understanding end-product goals (management recommendations) and user-friendly software can make these estimates and predictions functional and available in a timely manner to farmers and crop advisors. Lastly, weed management decisions made in conjunction with these estimates and predictions increase the efficiency of farming operations.

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FIGURE LEGENDS

Figure 1. Costs of weed control recommendations made by *WeedSim*, a weed management decision aid software program (Swinton and King 1994), based on varying seed bank densities of *Setaria faberi* in a maize crop. Note that individual recommendations are stable within relatively wide ranges of seed bank densities.

Figure 2. Coefficient of variation of seed bank densities and associated sample (soil core) numbers from which the data were derived. Data originated from a commercial field (80 x 800 m) with a maize-soybean rotation located on the farm of Mr. Ronald Barsness in Pope County, Minnesota. Lines represent the average coefficients of variation of ten random sortings of the data from 96 cores that were distributed orignally in an evenly spaced 4 x 24 grid. Note that variance stabilizes earlier for the most common species, *Setaria viridis,* than for the relatively sparse populations of *Amaranthus retroflexus*. Regardless of the difference between the species, 20 to 40 soil cores would appear adequate to capture the requisite seed bank information for each species.

Figure 3. Mid-season control of *Chenopodium album* due to mechanical seedbed preparation with a field cultivator and harrow at various percentages of predicted emergence at the time of crop sowing. No herbicides were applied, but areas between soybean rows were cultivated about six weeks after sowing. Adpated from Forcella et al. (1993).

Figure 4. Early-season control of *Setaria viridis* (Fox) and *Amaranthus retroflexus* (Pig) with the preemergence herbicides, metolachlor (2.5 kg ai ha^{-1}) and metribuzin (0.5 kg ai ha^{-1}), respectively. Herbicides were applied when each species was predicted to be at one of five levels of seedling emergence.

Figure 5. Relative density (opposite of percent control) of *Setaria* spp. when either rotary hoeing (R.H.) or interrow cultivation (Cult.) was performed at varying emergence percentages. G/Y-95 and G/Y-96 refer to mixed *S. viridis* and *S. glauca* populations in western Minnesota during 1995 and 1996; Gia-MN refers to *S. faberi* populations from eastern Minnesota during 1989-91; and Yel-NY refers to *S. glauca* from New York state. Adapted from Oriade and Forcella (1998).

A SIMPLE TECHNIQUE FOR PREDICTING FUTURE WEED PROBLEMS AND CHOOSING THE BEST WEED MANAGEMENT PRACTICES

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Summary

Farmers must be able to predict the severity and species composition of future weed infestations in order to make the most appropriate weed management decisions. Simple techniques can be used by even small farmers to predict future weed problems. Assuming that a farmer does a reasonable job of managing weeds occurring in fields each year, previous weed infestations can be used to predict future weed infestations. By annually leaving small areas in each field temporarily unweeded and keeping records of overall weed density and species present, weed severity trends can be established and used to improve future weed management. After evaluation, weeds should be removed from the unweeded areas to prevent seed production. Slight crop yield losses which might occur in the unweeded areas will be insignificant when compared to the benefits provided by improved weed management decisions. Alternatively, soil samples could be taken annually from fields, weeds allowed to germinate, and weed seedlings counted. Again by keeping records, changes in weed populations can be anticipated.

Even better weed management decisions are possible if the magnitude of crop yield losses caused by different levels of weed infestation can be predicted. Even small farmers can conduct yield loss studies by implementing different levels of weed management on small plots, and documenting resulting differences in weed severity and crop yields. By knowing the effects of different levels of weed severity on crop yield, economic thresholds can be developed to facilitate appropriate and profitable weed management decisions.

I. Introduction

Because of years of good weed management, many Wisconsin field corn (Zea mays L.), sweet corn (Zea mays L.) and soybean (Glycine max L.) fields have very low weed populations (Wagner, 1992). These fields are prime candidates for applications of herbicides at reduced rates, an important practice in a state where herbicide contamination of groundwater is wide spread (LeMasters and Harrar, 1990). Unfortunately, most growers cannot predict a field's actual weed pressure. They see the weeds which escape management practices, but don't know how many and which species of weeds would have been present without any weed control measures. Lack of this critical information leads to excessive application of herbicides. Having conducted weed seed bank studies, University of Wisconsin-Madison weed scientists understood the difficulty and expense involved with sampling, separating and counting weed seeds in field soils (Forcella, 1992; Kropac, 1966; Schafer and Chilcote, 1970). They also recognized the great difficulty in predicting how many seeds found in soil samples will actually germinate and grow in individual fields each cropping season. They had also conducted crop-weed interference studies, and understood the great variability in crop yield reductions resulting from weed interference in different years and at different locations (Bauer, et al., 1991; Mortenson and Coble, 1989). **There had to be a simpler process by which farmers could predict the effects of future weed populations on crop yields and to help them make the most appropriate weed management decisions!**

Assumptions upon which a simpler technique was based: In the process of developing a simpler procedure for predicting the effects of future weed problems, the University of Wisconsin-Madison weed scientists made the following assumptions:

1. As long as escaped weeds are not allowed to seed profusely, the best predictor of future weed problems is knowledge of previous weed problems. By keeping long-term records of weed problems in replicated untreated check areas within each field, growers should be able to not only anticipate severity of weed infestations, but recognize early changes in species composition of weed populations.

2. Severity of weed problems can be monitored by making "weed pressure" (WP) ratings. WP is defined as the visual estimate of the percentage which weeds contribute to the total volume of both crop and weeds in a plot. Volume estimates were made by considering simultaneously both height of and surface area covered by crop and weed species, respectively. A WP of 0 indicated the total absence of weeds and 100 indicated the total absence of crop plants.

3. Crop yield reductions from all weed species are similar when compared on a WP rather than number per area (population) basis.

4. A given weed population will produce similar WP ratings in field corn, sweet corn and soybeans.

Basis for the assumptions: Experience has shown that each farmer's weed problems reflect environmental conditions and agronomic practices unique to individual fields. For example soil texture, fertility, moisture, pH, salt content and tilth vary from field to field. Individual farmers conduct tillage and other cultural practices differently in given fields, and certainly differently than other farmers. It would be nearly impossible to model such variability. So it was proposed that previous history might be a more useful predictor.

Prior to 1977, most U.S. weed scientists evaluated herbicide efficacy in field trials by rating as groups all broadleaf and grass weeds. In 1977, however, the U.S. Environmental Protection Agency (EPA) directed that control of weed species be rated individually. Wisconsin field weed management studies are always taken to yield. Crop injury, and broadleaf and grass control ratings easily could be compared to determine the cause of yield variation. But, when the EPA required each weed species to be rated separately, often eight to twelve variables needed to be considered when assessing treatment performance. To simplify the assessment of factors affecting crop yields, University of Wisconsin-Madison researchers developed the simple visual assessment described above as WP.

WP was visually estimated and crop yields directly measured in field corn, sweet corn, and soybean herbicide efficacy studies conducted from 1977 to 1981, and in 1990 (Harvey and Wagner, 1994). Data from plots in which the herbicide treatment was observed to injure the crop and from plots where high rates of herbicide could potentially injure the crop were omitted from the evaluations. Data from 1640 field corn, 138 sweet corn, and 1374 soybean treatments were analyzed. Percent crop yield reduction (YLDRED) for all treatments were calculated relative to yields from either hand-weeded check plots or the best treatment in each trial. Linear regression analyses of field and sweet corn YLDRED and WP were significant

(P<0.001), with regression equations of YLDRED = 0.851WP (r^2 = 0.70) and YLDRED = 0.85WP (r^2 = 0.66), respectively. Nonlinear regression analysis of YLDRED and WP data from all 1374 soybean treatments were significant; however, a linear regression of those 1154 soybean treatments with WP ratings of 30 or less was also significant (P<0.001) and produced a more easily interpreted regression equation (YLDRED = 2.03WP, and r^2=0.45).

WP was determined in 20 southern Wisconsin fields in both 1990 and 1991 using the technique described below (Wagner, 1992). Mean WP values for the 20 fields monitored in both 1990 and 1991 were 23 and 25, respectively. WP values were relatively low (less than 10) in 47% and 65% of the fields monitored in 1990 and 1991, respectively. WP values ranged from 0 to 92 in 1990, and 1 to 95 in 1991. A significant regression (r^2 = 0.89, p<0.001) between 1990 and 1991 WP values from the 20 fields supported the theory that WP values could be used to predict future weed problems.

The herbicide efficacy trials used to calculate WP and YLDRED regressions were conducted at different locations, in years with substantially different rainfall, with one or more different weed species, and with different crop cultivars. Despite these differences, regression of WP and YLDRED were always highly significant. This supports the assumption that crop yield reductions from all weeds are similar when compared using WP values. In 1990 and 1991, replicated field corn, sweet corn and soybean plots were established without weed management in the same field. WP values were similar when all three crops were planted in rows spaced 76 cm apart, supporting the hypothesis that a given weed population will produce similar WP ratings in those crops.

<u>The proposed technique for documenting field WP</u>: A simple technique was developed, field tested, and an extension bulletin describing it published and distributed to farmers and crop consultants (Harvey, 1993). Farmers and crop consultants can be trained easily to use the technique, and similar procedures can probably be used anywhere in the world.

II. Collecting field data. Leave approximately 3 by 3 m untreated check areas in at least three representative locations within each field. This can be easily done by spreading plastic tarps on the ground prior to herbicide application, or by simply turning off one section of spray boom for a short distance at appropriate sites in the field during herbicide application. Remove plastic tarps shortly after spraying. Flag or stake the check areas so they can be easily located later. Global Positioning System (GPS) instrumentation can also be used to locate untreated checks. Success depends upon letting a weed population germinate which is representative of the field as affected by site specific factors such as soil type, soil tilth, soil fertility, and standard tillage and seedbed preparation practices. When field or sweet corn plants are 60 to 75 cm tall, or soybean plants are 30 to 40 cm tall (approximately 40 days after planting and typically just prior to canopy closure), estimate WP in each check area. At the same time, identify the primary weed species present in each untreated check area and estimate their relative contributions to total WP. Keep long-term records of WP and weed species data for each field.

If the standard practice is to rotary hoe and/or cultivate the field, then rotary hoe and/or cultivate right through the check areas. The resulting WP estimates will then help determine what weed management practices are needed beyond the mechanical practices. If it is uncertain whether the field will be rotary hoed and/or cultivated in future years, then lift these tillage tools before crossing the check areas.

After WP estimates have been obtained, use a hand sprayer to apply a 2% solution of glyphosate to the untreated check areas. Alternatively, weeds can be removed by manual weeding. This will prevent weeds in the untreated areas from producing seed and increasing future problems. Don't worry if the crop in the untreated check areas is killed or injured by the hand spraying. The value of damaged crop is very low relative to the benefits gained by collecting WP estimates. While you have glyphosate in the hand sprayer, use the left over mixture to control patches of perennial weeds growing in the field.

III. Predicting crop yield losses from uncontrolled weeds. Use Table 1 to predicted % crop yield loss if no weed management program is implemented on a field. This table was derived from University of Wisconsin-Madison weed control trials conducted over a six-year period including 1,640 field corn, 138 sweet corn and 1,374 soybean treatments (Harvey and Wagner, 1994). Multiply the predicted % yield loss by a reasonable yield goal and the anticipated unit price to give a predicted monetary loss. Growers must recognize that they will lose money if the value of their expected yield loss is less than the cost of their weed management program.

TABLE 1. Anticipated crop yield losses from various weed pressures with no weed control program.

Weed pressure rating	Severity of weed problem	Predicted yield loss: Field or sweet corn	Predicted yield loss: Soybeans
5	Slight	4%	10%
10	Low	9%	20%
20	Moderate	17%	36%
40	Severe	34%	54%
80	Very severe	68%	63%

IV. Choosing a management program. Unlike many "threshhold" models, this simple technique does not imply that a grower need not control weeds. Rather, it helps growers choose a weed management strategy which does not cost more than the predicted monetary loss due to uncontrolled weeds. When calculating costs of weed management options, include costs of mechanical practices such as rotary hoeing and cultivating, costs of herbicide applications, and costs of herbicides. The list of weeds present in each field can be used to select the most effective management options for the anticipated weed spectrum. Remember, when weed pressure is light, use of reduced herbicide rates is most feasible.

Examples of how the simple technique can be used:

Field 1. Records show that Field 1 is infested with giant foxtail (Setaria faberi Herrm.), redroot pigweed (Amaranthus retroflexus L.), velvetleaf (Abutilon theophrasti Medicus) and common lambsquarters (Chenopodium album L.). Average WP ratings over the past three years were 6, 8 and 7, respectively, and contributions to WP from giant foxtail, redroot pigweed, velvetleaf and common lambsquarters were approximately 40%, 25%, 20% and 15%, respectively, in all three years. Next year's predicted WP is 7, thus expected yield loss in the absence of management is about 6% for field or sweet corn and 14% for soybeans. Calculate the potential loss in value of the crop to be grown. Select a management strategy with activity against the four weeds expected to grow in the field which costs less than the potential loss.

Field 2. Records show that average WP ratings over the last three years in Field 2 were 4, 12 and 20, respectively. Velvetleaf, wild-proso millet (Panicum milliaceum L.), eastern black nightshade (Solanum ptycanthum Dun.) and redroot pigweed made up 50%, 20%, 15% and 15% of the total WP three years ago. But, wild-proso millet made up 60% and 85% of the total WP two and one year ago, respectively. Thus, WP and the contribution of wild-proso millet to WP have been increasing. Weed management practices must be improved! Anticipate a WP greater than 20, next year. Expected yield loss without treatment would be about 17% in field and sweet corn and 33% in soybean. Wild-proso millet is most easily controlled in soybean (Harvey and Porter, 1990). Consider growing that crop and using an appropriate treatment which controls that weed as well as the other species present.

Field 3. Field 3 is always cultivated when planted to row crops. Therefore, the three check areas in the field were cultivated prior to estimating weed pressure. WP was 2 and 1, three and two years ago when the field was cropped to corn and soybean, respectively. Primary weed species observed in the cultivated check plots were common lambsquarters, giant foxtail and velvetleaf and relative proportions did not change greatly between seasons. Last year, winter wheat was grown in the field and a system for estimating WP in that crop was not available. Since summer annual weeds which typically infest corn and soybean are suppressed in winter wheat, ignore last year's wheat crop, and anticipate a WP next year of 1 or 2. Expected yield losses with a cultivation for weed control would be about 2% in field or sweet corn and 4% in soybean. This field is an excellent candidate for low-input weed management. Consider options like combining rotary hoeing with multiple cultivations for a completely mechanical management program, using postemergence herbicides only as necessary to control weeds which escape cultivation, or using reduced rates of soil-applied herbicides in combination with timely cultivation.

Other benefits of using this simple technique: In the U.S., farmers frequently seek compensation from commercial herbicide applicators or chemical manufacturers if herbicides fail to control weeds or injure crops. Fair settlement of these complaints could be facilitated if untreated check areas were left in fields. Crop and weed growth could then be directly compared in both treated and untreated areas within the same field. In recent years, local, state and federal governmental agencies have passed rules restricting use of important weed management tools (e.g. burning, tillage and chemicals). When testifying at hearings during the rule making process, farmers frequently are unable to document the need for the threatened tools. If this simple technique were used routinely, farmers could present records of weed severity, species present, predicted yield losses, etc. This information would facilitate the risk-benefit analyses required for government to make responsible regulatory decisions.

Alternative methods to predict weed infestations: Visually observing WP in nontreated areas within a field is only one way to predict future weed infestation. In 1990 and 1991, Wagner and Harvey compared different methods of predicting future weed problems. These included collecting and screening soil samples from fields and identifying and counting weed seeds, placing soil samples collected from fields in a greenhouse and identifying and counting weed seedlings which germinated, identifying and counting weed seedlings germinating in nontreated areas within fields, harvesting and measuring biomass of individual weed species growing in nontreated areas within fields, and estimating WP. Regression coefficients for weed seed counts, greenhouse emergence counts, field weed seedling counts, field weed biomass weights, and WP for 20 fields between 1990 and 1991 were 0.85, 0.69, 0.5, 0.96 and 0.89, respectively. Separating, identifying and counting weed seeds was the most time consuming process, while estimating WP was the most efficient. Field weed seedling counts was the least useful, perhaps because environmental conditions varied between years, and the first weed species germinating each year suppressed emergence of other species. But, all of these monitoring techniques could probably be developed into useful prediction systems!

Application of this simple technique in developing countries: Unfortunately, the simple technique as developed for use by Wisconsin farmers is not useful directly by farmers elsewhere. This is because the predicted crop yield loss values listed in Table 1 were obtained from Wisconsin field corn, sweet corn and soybean field trials. Even if these crops are grown elsewhere, new yield loss prediction equations must be derived for each geographical area. But even without the yield loss predictions, keeping records of weed severity and which species are present for individual fields will help farmers make more knowledgeable management decisions. If the "farmer field school" concept is used to teach principles of sound weed management to farmers in developing countries, components of this technique could easily become an important part of the curriculum. Farmers could be trained to scout fields, determine WP, and identify the weed species present. If WP estimates were not appropriate for the cropping system, an alternative procedure for predicting weed severity could be implemented. For example, field schools participants could collect soil samples from various fields, place the soil in containers, and identify and count weed seedlings which germinate. This would help teach weed seedling identification, while demonstrating which fields had the most severe weed infestations. If differences in weed infestations were apparent, part of the learning experience might be to compare previous management of respective fields in an attempt to identify more effective yet locally practical weed management practices. At the same time, simple protocols could be prepared to assist farmers participating in field schools to conduct their own crop yield loss studies. Results from a number of studies conducted within a geographical region could be combined to produce crop yield loss prediction tables. Thus, field school participants could develop their own simple techniques to facilitate rational and responsible weed management.

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FORECASTING GROWTH OF WEED POPULATIONS

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Summary

In order to plan and to implement new, improved, weed management systems, farmers should take into consideration the potential for growth of weed populations. This type of information can be reached either, by carrying out long term experiments or by the use of modelling techniques. Long term studies may yield useful indications of the population trends in the short term, having a good potential for practical use at farm level. However, this approach presents numerous limitations. Using the results of demographic studies coupled with population models may allow weed specialists to make `reasonable predictions´ on the growth of weed populations under different control strategies. This approach is relatively simple and very flexible, being suitable to be used in developing countries (DC). However, constructing simple models, without sacrificing realism or precision, still represents a great challenge for Weed Science. In order achieve this goal, modeling experts from the developed world should work in close relation with weed control specialists from DC. These local experts should be trained in the use of these new tools in short courses at regional level.

Using the knowledge on population dynamics of weeds for management purposes is illustrated with various examples. This knowledge is used: a) for short term decision making, b) for developing cropping systems that prevent growth of weed problems, and c) for evaluating technical and economic consequences of various management strategies. The results shown illustrate the importance of forecasting as a basic component of weed management systems.

Although most of the biological knowledge can not be used directly by farmers, weed researchers from DC could use this knowledge to generate qualitative information on the likely behaviour of the most troublesome weeds in local systems. This information would help farmers to plan their cropping systems and to take other related decisions.

I. Introduction

In order to implement a weed management system, farmers and technical advisors usually consider three major factors: a) the current abundance and distribution of various weeds in a given field; b) the risks of crop losses caused by those weeds; c) the predicted efficacy of various control options and their economic costs.

Although these three considerations are important, they are not sufficient. If our aim is to implement production systems that are sustainable, we should consider these three factors within an overall long-term strategy for weed management.

In order to develop any type of strategy, we need to have a minimum understanding of the temporal and spatial behaviour of weed populations, both, in the absence of control measures and in response to various types of control practices.

Getting this type of information is not an easy task. In the developed world, this knowledge has been commonly gathered either, through the use of long term experiments or through the use of demographic studies coupled with simulation models of population dynamics. Both methods have, intrinsically, merits and pitfalls. The potential and the limitations of these forecasting tools should be particularly considered when trying to use them in the developing world.

The present work tries to offer answers to two basic questions: a) how to estimate potential changes in weed populations?, and b) how this knowledge can be used in weed management?

II. Using long term experiments for weed forecasting

Traditionally, information regarding the likely evolution of weed populations has been reached through the use of long-term experiments involving different weed management options. Although these experiments can consider the whole set of weed species present in the field (e.g. Popay *et al,* 1994) it is generally preferred to center the investigations in a single weed of particular importance. This is the case of the numerous studies conducted on the population dynamics of *Avena fatua* in England (Selman, 1970; Wilson, 1978, 1981, 1985). In one of the best known pieces of work, Selman (1970) studied over a period a five years the effect of different control programs -early planting of spring barley, late planting, early planting with herbicide,..- on the evolution of seedling densities of this species. Based on these results, he calculated the average annual rate of increase of the population ($\lambda = N_{t+1} / N_t$) for each situation. Using these simple values, he was able to simulate the temporal changes in the density of *Avena fatua* (Fig 1). The model used merely describes changes in seedling densities at 1-year intervals. It is, basically, a discrete exponential model, with population growth being measured by λ values. As an example, the effect of using an early sowing of a spring barley crop was simulated by making λ = 2.74 (the population increases annually by a 274%). In contrast, using a late sown crop was simulated by using an λ value of 0.40 (the population decreases annually by 60%). These values could be modified (reduced) to take into account the effect of herbicides of poor or good efficacy. In a similar way, higher or lower values could be assigned to simulate good or bad seasons of seed production.

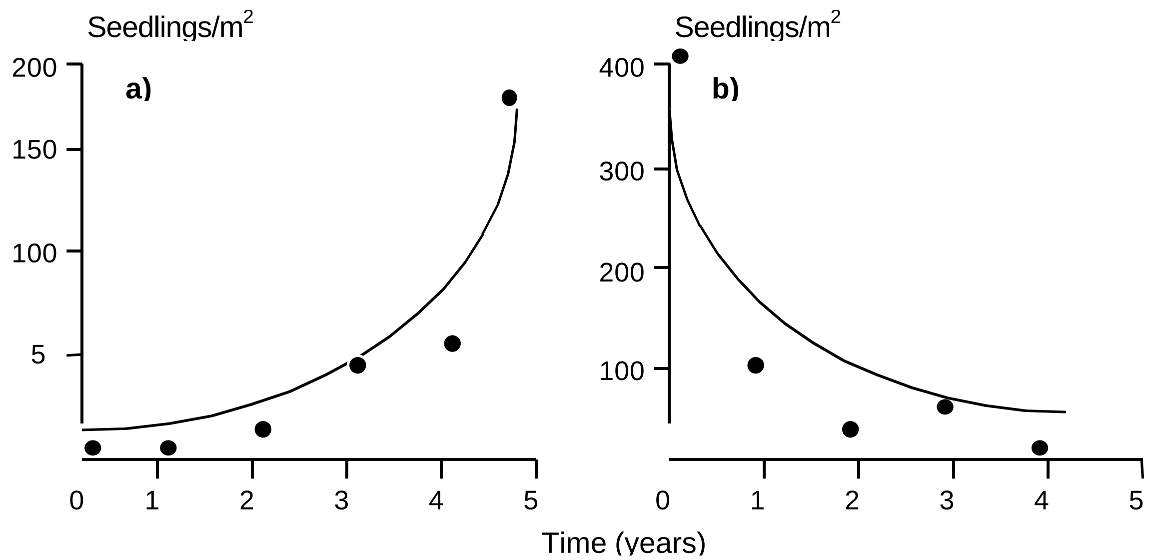

Fig. 1. Dynamics of *Avena fatua* in consecutive crops of spring barley: a) early sown crop; b) late sown crop. Exponential curves have been fitted by regression (after Cousens & Mortimer, 1995)

This approach has numerous drawbacks: it requires several years of costly experimentation, it can not consider a large number of control options, the results are highly dependent on the conditions present in a given site and during a certain time and a given period, getting answers to urgent questions may require many years, etc. (Cousens & Mortimer, 1995). On the other hand, the simple models derived have to make numerous assumptions: the individuals in the population are widely spaced (there is not interference among them), there are not limitations for population growth, population behaviour is always the same (independently of environmental conditions)....In spite of all these limitations, the predictions obtained in this way give useful indications on the population trends in the short-term. Since most farm management decisions are made in this time scale, these type of models may offer some potential for practical use at farm level.

III. Using models for weed forecasting

An alternative approach to the use of field experimentation is the use of mathematical modeling. Computer models, based on a good experimental knowledge of the behaviour of weed populations, may allow us to design and to evaluate (both, biologically and economically) new, improved, strategies for weed management.

Before going any further about modeling, a word of caution. As Cousens & Mortimer (1995) pointed out, modeling can not tell us what *will* happen; it only can be used to deduce what *should* happen. If our model is good and, more important, if our data and our understanding of the system are sound, we should be able to make *reasonable predictions*. The difference between a prediction and pure guesswork is the reliance on data and on understanding generated from previous research. This difference is crucial. Weed control strategies should not be developed based on "educated" guesses. They need to based on "reasonable" predictions.

The level of complexity of a model is conditioned by the human and financial resources available to construct it. For weed scientists and technologists working in developing countries, constructing "robust" mechanistic models (based on a large number of well structured state variables and on the availability of a large amount of high-quality data) is clearly outside their current possibilities. In this regard, it would be advisable to concentrate on the development of relatively simple models that were able to yield reasonably good predictions. In this regard, "demographic" models offer a good compromise between the simplicity (but lack of predictive power) of the totally empirical model described in the previous section and the complexity (but high research requirements) of mechanistic models. On the other hand, these models can be written using well known computer programs (such as Excel), they can be parameterised without an intensive amount of field work and they can be easily understood by non-experts.

In demographic models, the life-cycle of the species is divided into a number of discrete stages, with gains and losses from one stage to the next being controlled by "valves" that regulate this transfer of individuals (Kropff et al., 1996)(Fig 2).

Each year, a portion *g* of the seeds present in the soil (St) moves to the next functional stage through germination and emergence. Later in the life-cycle, a portion *k* of the emerged seedlings (Zt) may be destroyed by natural or artificial (tillage, herbicides) weed control processes, leaving a relatively low number of adult plants alive (Pt). The reproduction of these plants, determined by their mean fecundity *f*, will usually result in the production of an abundant seed rain (Rt). These new seeds will join the seed bank still present in the soil (after seed removal by germination, *g*, and by mortality, *m*) to form a new seed bank (S_{t+1}).

As in the case of Selman`s model, this basic demographic model makes various important assumptions: there is only one cohort of plants (a single period of emergence), weed density is low enough to avoid density dependent regulation, there are not seed losses through predation, harvesting machinery or stubble burning, weeds are uniformly distributed and they do not move in or out of the field. Obviously, real world systems are not as simple. In those cases where the above mentioned assumptions are likely to be wrong, we will have to add new attachments to the model.

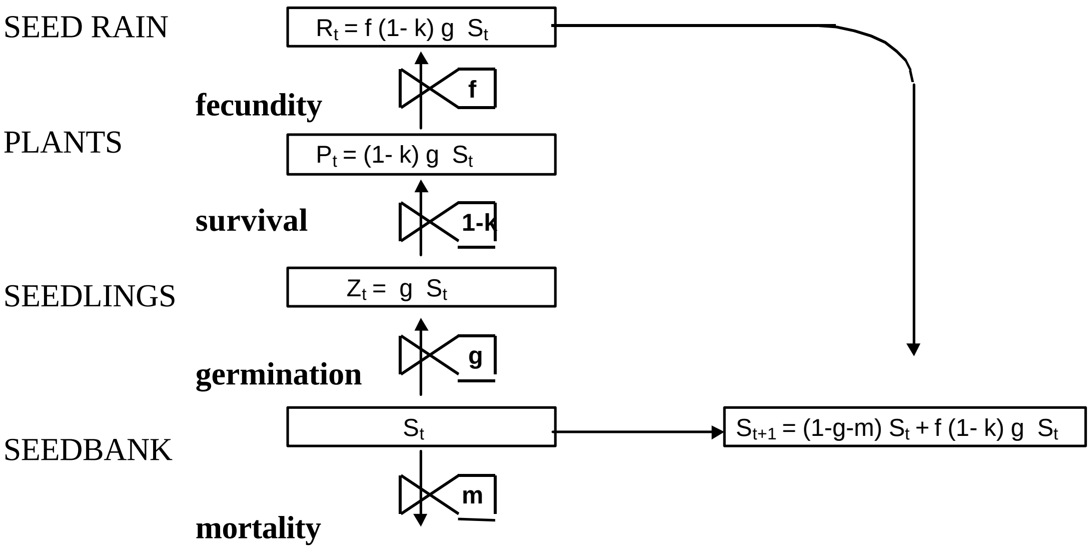

Fig 2. Diagrammatic model of the population dynamics of an annual weed. Inside the boxes: functional relationships defining the number of individuals present in each stage at each moment.

For example, if weed emergence does not take place as a single event but as a continuous process, we will have to incorporate into the model the age structure of the population. In order to do that, the various cohorts emerging at different times of the year can be defined by different rates of germination, g_i, and assigned with different probabilities of survival, K_i, and different fecundities, f_i. The total rate of each process will be defined by the summation of the rates of all the cohorts (e.g. $Z_{t,i} = \sum S_{t,i}\ g_i$) (Gonzalez Andujar & Fernandez-Quintanilla, 1991). Alternatively, the age structure may be described using matrix models, a method somewhat more complicated but offering more possibilities for future expansion of the model (Cousens & Mortimer, 1995; Maxwell *et al*., 1988).

If weed density is high enough to result in intraspecific competition, this factor should be considered. The effect of weed density on the average reproduction per plant, *f*, can be introduced into the model by the commonly used rectangular hyperbola:

$$f = \frac{a}{1 + a/b\ Pt}$$

where *a* is the production of viable seeds per plant at low densities and *b* is the maximum seed production per unit area at high weed densities (Kropff et al., 1996).

Frequently, weeds are not uniformly distributed in the space but grouped in patches. Furthermore, they are not static; they move in the field by different means. One step further in the modeling process may be the inclusion of space. This feature would allow to consider spatial gradients in density and to simulate the spread of weeds (Ballare *et al*, 1987; Maxwell & Ghersa, 1992).

Demographic models can be constructed as simple or as complex as the researcher decides. In the process towards a higher complexity, the modeller must act parsimonously, adding only the elements strictly necessary to reach the proposed objective.

IV. Using population dynamics knowledge for weed management

Farmers, acting as weed managers, should center their efforts in defining the best practices available in order to minimize the rate of increase of weed populations. In this regard, population models can be used to derive the desirable frequency of application of herbicides, the minimum doses required to attain a certain population trend, the desirable frequency of inclusion of brake crops in a given rotation, the minimum frequency of ploughing in a no-tillage system, etc.

Different types of models will yield different types of results. Simple models, such as that used by Selman (1970), will probably result in very simple 2-way tables that could be used by weed managers to estimate the likely outcomes of different situations (Table 1). In this particular case, the average rate of population growth of *Avena fatua* is predicted to be 2.5 in the case of an early sowing of spring barley, 0.29 in the case of a late sowing and 0.40 in the case of early plantings sprayed with the herbicide triallate. "Best case" scenarios would represent the situations where weed seed production is limited by unfavorable climatic conditions or high competitiveness of the crop and where seed survivorship and germination is low as a result of an adequate management of crop residues and soils. By the contrary, "worst case" scenarios include those situations where climatic conditions favor seed production, crop competitiveness is low and stubble and soil management practices favor seed persistence and germination.

	BEST CASE	**AVERAGE**	**WORST CASE**
Early sowing	x 1.30	x 2.50	x 6.00
Late sowing	x 0.14	x 0.29	x 0.68
Early sow.; Tri-allate	x 0.20	x 0.40	x 1.00

Table 1. Potential for annual growth of populations of *Avena fatua* in different scenarios (after Selman, 1977)

Although this simple approach does not allow the weed manager to predict what will happen in the long term, this may not be a serious drawback. Planning long term scenarios and weed control programs is, anyhow, hampered by the unpredictability of climatic and economic conditions.

One of the advantages of demographic models is that they can be easily expanded to include a large variety of factors. As an example, the above mentioned population dynamics model for *Avena sterilis* can be easily integrated with competition and economic submodels in order to evaluate -technically and economically- the effects of different management strategies (Gonzalez-Andujar & Fernandez-Quintanilla, 1993). The simulation results obtained with this model (Table 2) indicate that, although the strategy that combines the use of a fallow year with herbicide applications in wheat years (Strategy 5) may result in optimum control of this weed, the highest net return in the long term is likely to be obtained with the continuous wheat/continuous herbicide approach (Strategy 3).

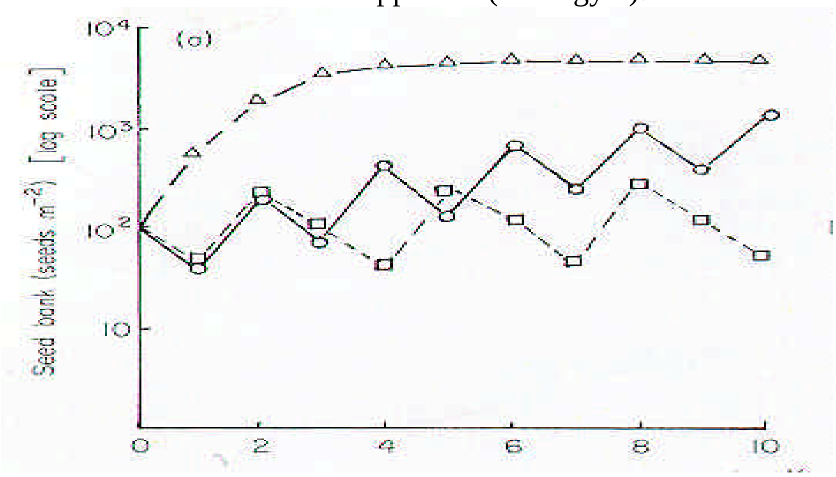

Fig. 4. Predicted changes in *Avena sterilis* populations under different cropping systems: (∇-----∇) continuous winter wheat; (O------O) fallow-winter wheat; (□------□) fallow- winter wheat- spring barley (after Gonzalez-Andujar & Fernandez-Quintanilla, 1991).

STRATEGY	1	2	3	4	5
Rotation[1]	W-W	W-W	W-W	F-W	F-W
Herbicide use[2]	0%	50%	100%	0%	50%
RESULTS					
Final population[3]	306	207	1.4	54	0.001
Net returns[4]	-54.0	-3.7	86.1	25.2	52.1

[1] W-W: continuous wheat; F-W: fallow-wheat; [2] % of years with herbicide use; [3] Number of *A. sterilis* plants/m2 after 10 years; [4] Annualized net returns over the 10 year period, US $ /ha/year

Table 2. Simulated performance of various strategies for the management of *Avena sterilis* populations in cereal crops (after Gonzalez-Andujar & Fernandez-Quintanilla, 1993)

V. Who would be the user of this type of knowledge?

Obviously, farmers in the developing world are not expected to use directly this type of knowledge. They do not have either, the basic information required (data on the dynamics of various weeds) and the basic tools to make the predictions (computers, computer expertise). However, local researchers can work with very simple models constructed by themselves or with the cooperation of experts from the developed world. This work should be aimed to generate qualitative information on the likely behaviour of some of the most troublesome weeds in the local cropping systems. This information would help the farmer to take short term decisions (to spray or not to spray) or to plan long term cropping programs. This approach has already been used in countries with an intermediate technological level (e.g. Argentina, Spain) with considerable success.

In order to train local researchers to use these modeling tools, short courses (one to two week duration) should be taught at regional level. This training, in the simplest case, would allow them to have an effective communication with modeling experts and to cooperate with them in the construction of models. In the best case, it with would allow them to select the model that better fits their specific needs, to adapt that model to local conditions and to use it to make their own simulations.

Conclusions and recommendations

- The forecast of weed populations should be a basic component of any weed management system.
- Using models to simulate the population dynamics of weeds offer a considerable potential as an aid tool for weed management. This statement is equally valid for developed and developing countries.
- In developing countries, existing limitations in human and financial resources makes advisable to use simple models based on relatively few parameters. Constructing these types of models, without sacrifying realism and precision, represents a great challenge for Weed Science.
- In order to achieve this goal, modeling experts from developed countries should work in very close relation with weed control experts from developing countries. Additionally, short courses should be taught at regional level in order to train local technicians in the use of these new tools.
- Due to the relatively high economic and human investment required for the development of these models, efforts should be concentrated in only a few of the most troublesome weeds at regional level (e.g. *Striga, Echinochloa, Cyperus, Orobanche*)

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ECONOMICS & MANAGEMENT

INFLUENCE OF WEED TIME OF EMERGENCE AND REMOVAL ON CROP YIELD LOSS

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Summary

The paper briefly reviews the aspects related to influence of the relative time of weed emergence and removal on crop yield loss. The importance of early plant growth in determining the intensity and outcome of the subsequent weed-crop competition is highlighted. The variability, in space and time, of the relationships between weed time of emergence and removal, weed density and crop yield loss area is discussed. The concept of the critical period is debated and it is concluded that the identification of a period alone does not provide information on how many or when control practices should be performed. Given the time dependence of the weed competitive effect, treatments carried out within this period cannot be regarded as having the same net margin and therefore there has to be an optimum time for one or more weed control tactics. The time density equivalent (TDE) approach could provide a solution to this problem. The need for more basic information on weed-crop competitivity and on environmental data in third world countries is stressed.

I. Introduction

In most of the less developed countries, agriculture employs more than three-quarters of the labour force and provides a major source of GDP with a share of 35-40% (Maskey, 1997). A crucial policy issue is how to raise the income of resource-poor farmers without despoiling the natural resource base. A holistic approach based on Integrated Pest Management (IPM) as well as on sound economic principles would provide a useful framework to protect both resources and farmers' income.

Since its adoption IPM, and its component Integrated Weed Management (IWM), has become the basis for all FAO plant protection activities because it contributes directly towards the achievement of sustainable agriculture in developing countries (Labrada and Parker, 1994). To successfully implement an IWM strategy, weed management should match the specific problems in a field and therefore some basic knowledge on weed and crop ecology and biology is needed to correctly predict the impact of a weed infestation on crop yield. In this context, weed-crop growth characteristics and the dynamics of weed emergence are important aspects (Akobundu, 1998). Many farmers in the developing world are unaware of several aspects of weed interference and of the best time for weed removal (Akobundu, 1998; Labrada, 1996 and 1998), although there are exceptions. Ellis-Jones *et al*. (1993) found widespread appreciation in Zimbabwe of the importance of early weeding for both weed suppression and improvement of rainfall infiltration.

Weed germination patterns generally result in cohorts of seedlings emerging over an extended period of time and are heavily influenced by weather conditions, soil type and cropping system (Vleeshouwers, 1997). The initial emergence time differs from year to year and varies according to the species ecological requirements (mainly temperature and soil moisture content - Forcella *et al*., 1997). It is also well-established, and has been experimentally quantified for several crops and types of weed infestation (Zimdahl, 1988; Berti *et al*., 1996), that the relative time of crop-weed emergence and the time of weed removal heavily influence crop production.

On small-scale farms in developing countries more than 50% of labour time is devoted to weeding, being mainly done by women and children in the farmer's family (Ellis-Jones *et al*., 1993; Akobundu, 1996). In traditional farming systems a knowledge of the so-called "critical period" of competition would enable farmers to make the most efficient use of the limited labour resources. In conditions of medium-high weed pressure, the critical period is approximately centred on the first one- third of the crop growing cycle. For example, several major field crops of temperate climes (e.g. maize, soybean, sunflower) take 100-140 days after emergence (DAE) to mature and the critical period is usually between 25 and 40 DAE (Zimdahl, 1988; Doll, 1994). Of course, the critical period varies with the relative competitivity of the crop and the weed infestation: the lower is the crop competitivity (and/or the higher the weed flora competitivity) the longer the period the crop must be kept weed free to prevent significant yield losses.

The aim of this paper is to give a brief review of the aspects relating to the influence of relative time of weed emergence and removal on crop yield loss.

II. Early Growth Stages

In agricultural environments, where the habitat is generally fertile, between two heavy disturbances the hierarchical place that a plant occupies, as well as being influenced by the potential adult size, is related to its capacity for capturing resources and is largely determined at early stages of development, i.e. during the exponential phase of growth (Sattin and Sartorato, 1997). Fisher and Miles (1973) theorised a three to eight fold increase in competitive advantage (depending on density and spatial arrangement) combining early emergence and rapid growth. Kropff and Spitters (1991) showed that the competitive strength of a species is largely determined quite early in the season by its share in leaf area at the moment when the crop canopy closes.

The potential growth of a plant during the exponential phase, expressed as weight (but leaf area could also be used), is a function of: a) its starting capital (i.e. seed reserve mass which is practically equal to the seed mass minus the seed coat), for many species the seed weight can be used as a good approximation; b) the relative growth rate (RGR) of the plant in a given environment; and c) the length of time for which this growth rate is maintained. The relative importance of these three factors depends upon the species and environmental factors. Some authors (Fenner, 1983; Sattin and Sartorato, 1997) have shown that these factors are negatively correlated (e.g. species with larger seeds tend to have lower RGR).

When plants are growing together and competing for resources, the influence of all the above factors on plant competitivity can be overwhelmed by the relative time of emergence. There is a vast literature showing that a few days delay in emergence can often create an unrecoverable gap between plants. It also appears that in hotter climates where the growing season is often shorter, as is found in many third world countries, the importance of early weed-crop competition is accentuated (Mohamed *et al*., 1997).

III. Relationships between crop yield loss and weed time of emergence and removal

Given the importance of early growth, the trend of the relationships between yield loss and weed time of emergence and removal can be easily understood. The competitive effect of a given density of weeds emerged with the crop depends strongly on the length of the period they remain in the field (i.e. the time of weed removal). The relationship between the duration of competition and crop yield reduction is approximately sigmoidal: weeds competing for a short period have little effect on crop yield; allowing the weeds to compete for a longer time, the yield reduction increases, until a plateau is reached corresponding to the yield loss caused by weeds competing over the entire growing cycle. Crops like maize and soybean show a relatively long initial period when the damage caused by weeds is relatively low, while most horticultural crops are more sensitive, as shown in Figure 1.

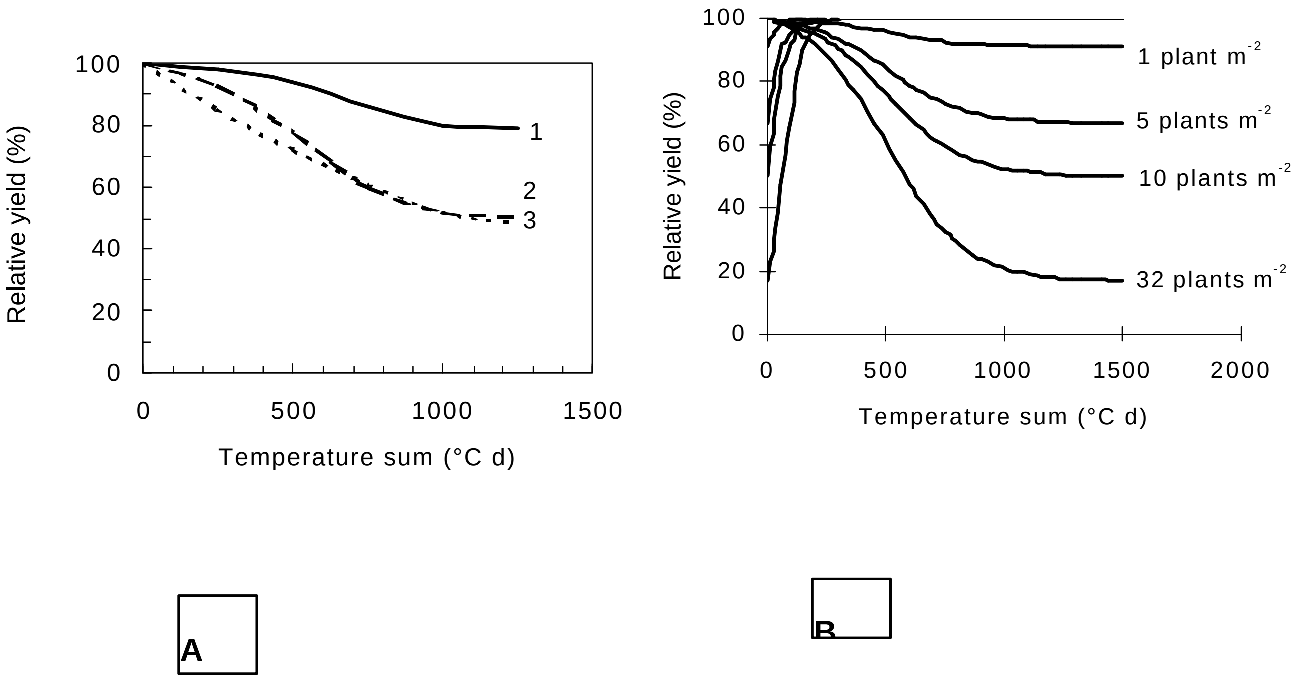


Figure 1. **A**: Crop relative yield, as a percentage of the weed-free test, as a function of duration of competition (i.e. time of weed removal) for a weed density of 10 plants m^{-2}. 1 = maize in competition with *Abutilon theophrasti* (Sattin *et al.*, 1992); 2 = soybean in competition with *Amaranthus cruentus* (Berti *et al.*, 1990); 3 = onions in competition with *Helianthus annuus* (Dunan *et al*., 1995). **B**: Soybean relative yield, as a percentage of the weed-free test, in relation to time of emergence, time of removal and density of *Amaranthus cruentus* (Berti *et al*., 1990).

The relationship between weed time of emergence and crop yield loss mirrors the curves in Figure 1A. Of course these relationships are influenced by weed density: for a specific weed time of emergence or removal, the higher the density the lower is the relative yield (Figure 1B).

Extending the above concepts to a mixed weed infestation that can be found in any cropped field, the yield can be expressed as a function of maximum yield of the crop kept weed-free, weed competitive load and time of emergence and removal of the weeds. The first two factors are clearly site-specific, while contrasting data have been reported for the variability of the weed-free period (WFP) and duration of tolerated competition (DTC) curves in different years and/or locations. The experiments designed to obtain this sort of information are tedious and very expensive. An important question is therefore how variable are these data in space and time. Using three data sets showing the effects of mixed weed infestations in maize, soybean and durum wheat and by means of the density equivalent approach (Berti and Zanin, 1994), Sattin *et al*. (1996) recently analysed the variability of DTC and WFP curves across reasonably homogeneous areas in temperate environments. Despite the differences in weed flora among the experiments within each data set, the pattern of these relationships appeared to depend more on crop characteristics than on the composition of the weed infestation. If these results are confirmed for other areas and crops, for a given area the prediction of yield loss caused by mixed weed infestation with any time of emergence and/or removal will require the knowledge of the weed free yield, the relationship weed competitive load -yield loss and only one set of parameters (i.e. only one large experiment) linked to the effects of time of weed emergence and removal. Information on weed competitive load-yield loss relationships already exists for several sites and crops and, even if unavailable, it is much less tedious to obtain compared to the determination of the relationships between DTC, WFP, weed density and crop yield loss.

IV. Critical period and optimum time for post-emergence application

The critical period has been defined as the period during which weeds must be controlled to prevent yield losses. Since the concept of critical period was introduced, it has been used to determine the period when control operations should be carried out to minimise yield losses for many crops (Zimdahl, 1988). Historically, critical periods have been calculated by mean separations (hereafter referred to as the classical approach) in experiments that evaluated the impact of time of weed emergence and time of removal on crop yields. Using the classical approach, it is possible to identify a period within which no statistically detectable yield losses occur. It has also been concluded that for most field crops it is unnecessary to control weeds in the first few weeks after crop and weed emergence (Zimdahl, 1988).

Several problems inherent in the classical approach have been pointed out and use of regression analysis (hereafter referred to as the functional approach) was suggested as a better alternative. In changing from the classical to functional approach, the existence of a period when weeds do not cause any yield reduction became doubtful due to the continuous relationship between yield loss and time of weed emergence and removal. To avoid this problem, fixed yield loss thresholds were used to define critical periods. (e.g. Van Acker *et al*., 1993). Within this framework it was concluded that early weed control is unnecessary (Hall *et al*., 1992). This conclusion was not the result of an accurate evaluation of when to start to control weeds, but of the way critical periods were calculated. The functional approach fails to recognize that since there is a continuous relationship between crop yield and time of weed removal, controlling weeds pre-plant or pre-emergence or post-emergence cannot be compared without considering yield losses that occur between planting and post-emergence control.

The establishment of a fixed yield loss threshold indirectly considers the economic aspect in the calculation of critical periods. Within this framework, Dunan *et al*. (1995) developed an economic approach to calculate critical period. They defined the economic critical period as the time interval when the marginal income of weed control is higher than cost of control and its limits are called early and late economic period thresholds.

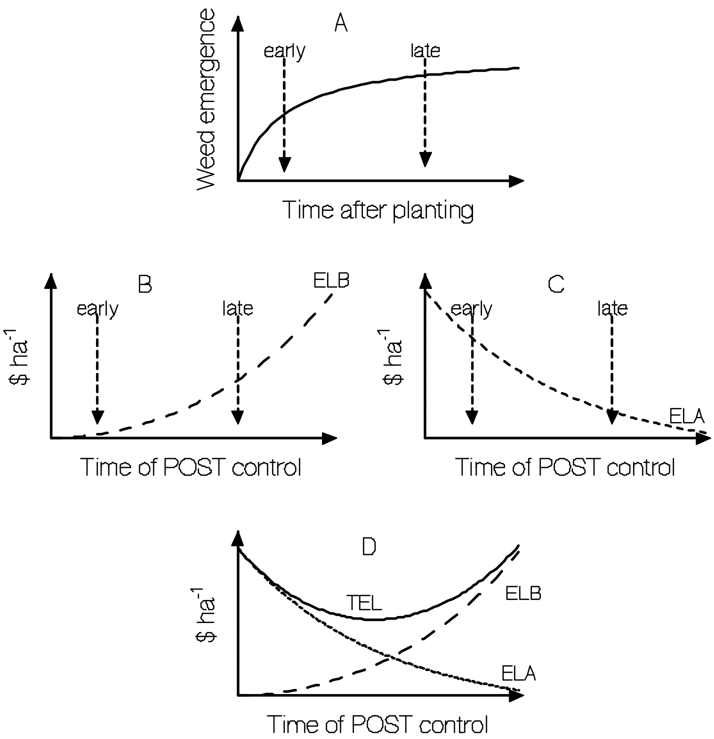


Figure 2. Theoretical representation of the concept of optimum time of application for post-emergence treatments. **(A)** Hypothetical pattern of weed emergence as a function of time after crop planting; **(B)** economic loss due to weeds emerged before the post-emergence treatment (ELB); **(C)** economic loss due to weeds emerging after the post-emergence treatment (ELA); and **(D)** total economic loss (TEL) as a function of time of control. Early and late represent two different times of post-emergence weed control and it is assumed that the efficacy of post-emergence treatment is 100%.

The period when weed control can be carried out starts before sowing with a pre-plant weed control tactic and continues until the phenological stage of the crop that precludes any further weed control. Within this time lapse the three approaches (classical, functional and economic) all define a period when weeds should be controlled.

However, identification of a period alone does not provide information on how many or when control practices should be performed. Considering the time dependence of the weed competitive effect, treatments carried out within this period cannot be regarded as having the same net margin (i.e. difference between the value of the crop with control minus the cost of treatment and the value of the crop without control) and therefore an optimum time for one or more weed control tactics exists which provides the highest net margin (Figure 2).

Weed emergence can begin from the moment of final seed-bed preparation and then continue while environmental conditions are favourable for the germination process. As previously shown, the time of weed emergence greatly affects weed competitiveness, with the first emerging weeds being far more competitive than the late emerging ones. Most post-emergence treatments have low or nil residual activity; because of this they can control the weed population present at the moment of application, but have little or no effect on subsequent germinations. The economic outcome of post-emergence treatments will vary according to the time of application and is related to the efficacy of the treatment, to the characteristics of the crop (WFP and DTC curves) and to the weed germination pattern.

As a first approximation, crop yield loss is given by the sum of the yield loss caused by weeds emerging before the treatment (competing with the crop until the treatment) and that caused by weeds emerging after the treatment (competing from emergence until harvest). These two yield losses follow opposite trends (Fig. 2). With an early treatment, the loss caused by the weeds emerged before the spraying is low because the duration of competition is short. On the other hand, a consistent number of weeds can germinate after the treatment and, remaining until harvest, can produce an important yield loss. With a late treatment, damage caused by weeds emerging after the treatment is reduced, but there is a marked increase in the damage due to the weeds emerging before the treatment. The sum of these two losses gives a total economic loss curve characterised by a minimum which identifies the optimum time of treatment (Berti *et al.*, 1996).

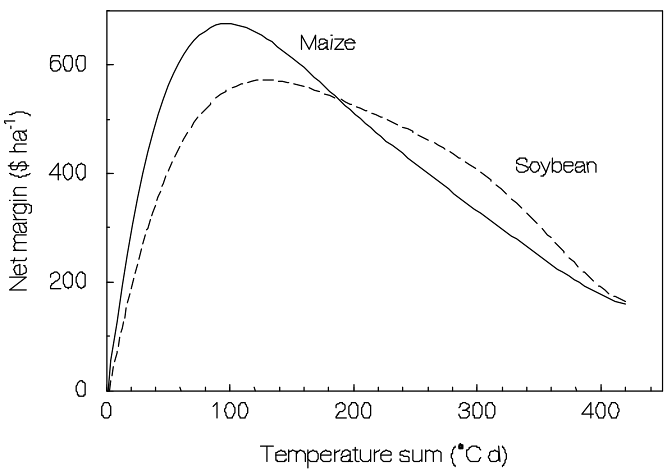


Figure 3. Relationships between time of application of a post-emergence treatment and net margin for maize and soybean. Maize: Weed-free yield = 10 t ha^{-1}; Cost of post treatment = 45 \$ ha^{-1}; Grain price = 155 \$ t^{-1}. Soybean: Weed-free yield = 4 t ha^{-1}; Cost of post treatment = 45 \$ ha^{-1}; Grain price = 250 \$ t^{-1}. For both crops a weed infestation capable of causing a yield loss of 50% if untreated was considered.

Figure 3 shows an example of these calculations for maize in the Po valley (Italy) and for soybean in southern Ontario – Canada (Sattin *et al.*, 1996). The curves were calculated using the Time Density Equivalent approach (TDE - Berti *et al.*, 1996) and the DTC and WFP relationships calculated by Sattin *et al.* (1996) were used. With the TDE approach, the weed population is divided in daily cohorts depending on their time of emergence. For each cohort the TDE is equal to the density of a cohort of weeds emerging with the crop and competing until harvest, giving the same yield loss as the considered cohort. TDEs can be considered additive and their sum is a Total Time Density Equivalent (TTDE), which gives a good estimate of the competitivity of the weed population depending on the emergence pattern, and, considering herbicide efficacy, on the time of treatment. The relationship between time of weed control and net margin depends on the pattern of weed emergence and on the competitiveness of the crop.

V. Case study: influence of the duration and timing of a weed control operation

Hand-weeding (pulling out and hoeing) and simple animal-drawn tools, are the main control methods in the developing world and they dominate in low input farming (Akobundu, 1998). Furthermore, hand-weeding is almost always done by women, often pregnant, and children. It is therefore particularly important to optimise the time when the operation starts and the amount of labour (i.e. the duration of the operation) devoted to weed control. An example of the labour requirement for three weeding systems in maize is given in table 1.

Table 1. Labour requirements for four weeding systems in Zimbabwe.

	Labour hours spent weeding per ha		
	Manual	Mechanical	Total
Hand weeding	132.5	0	132.5
Cultivator	52.2	16.2	68.4
Mouldboard plough	26.8	28.3	55.2

From Ellis-Jones *et al*. (1993).

To theoretically show the relative importance of: a) the time when weeding begins, b) the amount of labour available (i.e. the time required to weed a crop), c) the accuracy of hand weeding, simulations have been performed by means of the above-mentioned TDE approach. Maize was chosen because it is a widely cultivated crop in several developing countries. Considering that a complete set of information (WFP, DTC, weed emergence pattern, weather data) needed for the simulations was not found for a developing country, data from a Mediterranean environment (northern Italy) were used. A hypothetical weed infestation characterised by parameters of the Cousens' weed density-yield loss hyperbola (Cousens, 1985) equal to: i = 0.1 and a = 0.9, was considered. The initial weed density was 40 plants m^{-2}. If not controlled, the above infestation would have caused a yield loss of 83%.

The simulations (figure 4) show that, if only one control operation is possible, this must not be done too early. If needed, it is better to delay rather than anticipate the weeding. The duration of the weeding (i.e. time required to weed a certain area) seems to have a negligible effect on the minimum attainable yield loss, but it has some impact when the control is started early. The accuracy of hand weeding seems to play a not marginal role, as shown by the minimum attainable yields in figures 4A and B. It appears that even if the operation is done very carefully (kill rate equal to 1), with only one weed control the impact of early competition and of the weeds emerging after the operation is quite high (the minimum attainable yield loss is around 10%).

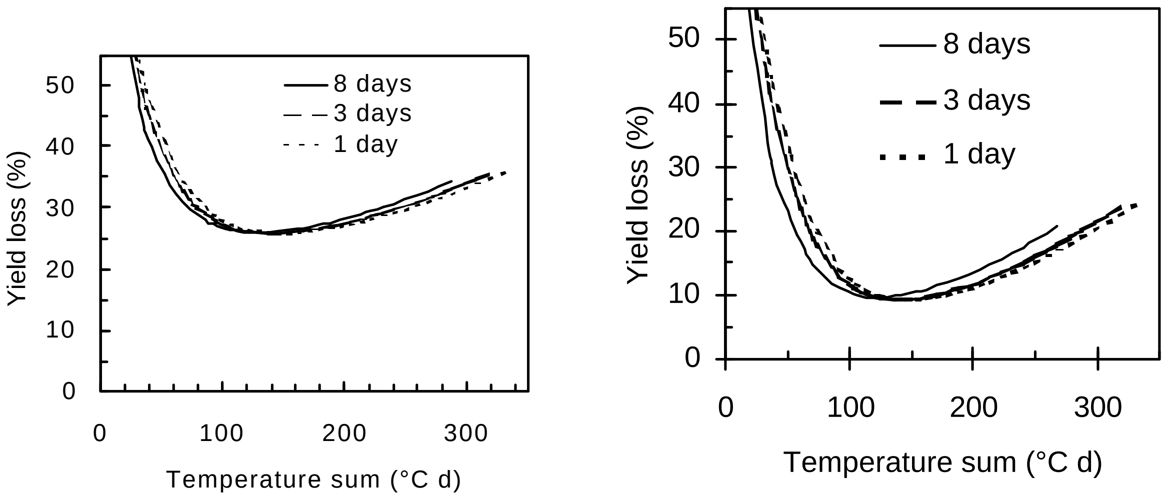
Conclusions

This brief review shows that the beginning of the growing cycle is of importance in determining the intensity and outcome of the subsequent weed-crop competition. The relative time of weed and crop emergence appears to be crucial and can overwhelm many other factors: a few days difference in emergence can create an unrecoverable gap between plants. In studying the effect of these variables (WPF, DTC, pattern of weed emergence) it is better to use the temperature sum rather than the number of days as independent variable. In this way the results from experiments carried out in different environments can be compared.

Any agronomic practice which delays weed emergence and favours a satisfactory crop establishment plays an important role.

There are indications that the variability (in space and time) of yield loss caused by mixed weed infestations can be relatively low. Therefore, if these results are confirmed for different areas and for various crops, for a reasonably homogeneous area, only a few relatively simple experiments are required to predict yield loss in relation to WFP, DTC and weed density.

The theoretical exercise done through the simulations using the TDE approach shows that simple models could give useful indications and provide a framework even in situations where the technological level is low (i.e. where hand weeding is prevalent). It would therefore be very useful to have, at least for the most important agricultural areas and crops, some basic data sets related to weed-crop competitivity and weather conditions.



A

B

Figure 4. Simulations of maize yield loss as a function of the time when the weed control operation begins. Three duration of the weed control operation are considered: 8 days per ha (it is assumed that to hand weed a hectare of maize it takes 132 hours – see table 1 -, i.e. 2 people working 8 hours per day); 3 days per ha (assuming the weeding is done part mechanically for 16 hours and part manually for 52 hours – see table 1 -, 3 people working per 8 hours for day would take about three days to weed a hectare; 1 day per ha (corresponds to a hypothetical herbicide treatment).
A: H (kill rate) = 0.95; **B**: H = 1. Weed-free yield = 2.5 t ha^{-1}, maximum yield loss = 83%.

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PRACTICAL USE OF ECONOMIC THRESHOLDS FOR WEEDS

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Summary

Weed control focusses on reducing actual competition and/or future build up of weed problems. In the developed world, herbicide use solves most weed problems. In Germany despite possible environmental problems connected with herbicides, an uneconomic over-use of herbicides in competitive crops, like cereals and oil seed rape became evident. The following development is taken as example for methods and results in weed research focussing on economic thresholds. Weed economic thresholds were derived and checked in various experimental approaches in the field. Economic thresholds are an adequate tool to further improve weed control in competitive crops with an intensive use of herbicides. In situations with less efficient and time consuming control, they can be a tool for stirring control intensity.

I. Introduction

The idea of thresholds for decisions in plant control was of central importance for the prime of IPM. Thresholds can be figured as a line or a better a range, which devides direct plant control tactics in either necessary or not. ´Necessity´ can be economically determined or by lacking possibilities to control the organisms later. Starting from principles in pest and disease control, in Germany the idea was soon transferred to weed control. Taking into account strong differences in the mode of interference and control between perennials and annuals, the work focusses completely on annual weeds.

Annual weeds offer some advantages compared to pests and diseases, since they do not migrate in the actual year, they have no strong potential for an exponential population development in the actual year and the organisms are easy to observe. However, there are also disadvantages: weeds are unequally distributed in the fields, the period of control is early compared to the period of damage and the existence of a seed bank transfers actual decisions into a long-term period with unknown consequences.

Shall these arguments encourage or discourage applied researchers to invest resources into any work around economic thresholds for weeds? An overview taking the development in Germany as example is given in order to extract general aspects focusing perspectives for the developing world.

II. Conditions

In Germany economic thresholds are connected with the idea to reduce herbicide use. The need and the perspectives were evaluated with data of weed control experiments of the German Plant Protection Service in cereals and oil seed rape. Generally competitive crops offer more perspectives to reduce control intensity than crops grown in rows. Weed growth is restricted by early developing crops and harvesting before ripeness of seeds restricts seed production of several weed species. In 25 to 68 % of the cases weed control gave no actual positive net return (Gerowitt *et al.* 1984, Wahmhoff 1990a). Connections between economic return and weed infestation were described, which indicate that the figures were not caused by control methods harming the crops.

Considering economic thresholds require to obtain an impression of the weed infestation. Therefore the existance of safe and powerful post-emergence control methods in the actual crop is of essential importance. In Germany, post emergence weed control in cereals, normally done with herbicides, is available.

The importance of safe post emergence control options for any economic threshold approach became evident in oil seed rape. The competitive crop offers possibilites to skip herbicide use, but until the mid of the eighties only pre-sowing and pre-emergence herbicides were available. With the introduction of post emergence herbicides in this crop, it became worthwile to think about weed economic thresholds.

Can the weed infestation of a field be assessed in a sufficient way? Taking into account results dealing with the spatial distribution in the fields, it is at least difficult and gives uncertain values (Niemann 1985, Pluschkell & Pallut 1996). In the near future opto-electronic instruments will probably help to reduce these problems. Using image analysis will give objective data of the cover of weeds and crops and may be done continiously (Gerhards *et al*. 1994), methods of GPS may support sophisticated use of weed maps (Nordmeyer & Niemann 1992). Meanwhile, still a pragmatic, low technical input, solutions is advised: To make a field assessment, which gives an overview, but can be done in a reasonable time. Taking around 30 spot-cheques with a mobile frame of 0.1 m² is recommended as guide value (Aid 1993). Small infestations are quickly assessed and offer most opportunities to skip control. The problems connected with patchiness should not be neglected. However, farmers have to decide anyway, the described field assessment offers a possibility to base the decision on actual infestation data. Farmers usually have an idea about their main species and are able to identify them in early growth stages, but the actual emergence, especially in low density ranges seems still unpredictable (Gerowitt & Heitefuss 1990b).

What should be known about the conditions **in the developing world**? In addition to an overview over the leading weed species in a region, an overview of the commonly used weed control techniques concerning form, time and efficiency is required. Weed species with specific opportunities, e.g. perennials, species which contaminate the products, species with massiv „migration“ into the system, makes it more difficult to reduce any threshold concept to an applicable approach. Information about crop husbandry will be helpful. The existence of a crop rotation with safe and efficient control methods in all crops will facilitate the use of economic thresholds. Intensive use of herbicides connected with competitive crops offers most opportunities. Thresholds may also be useful, if time or efficiency is lacking, in order to rank the necessity of weed control treatments.

III. Concepts

An “Economic threshold” has to consider variables of agronomy and economy, since the cost of control are compared with the expected losses caused by weeds. The latter can consist of yield and quality losses or a decreased harvesting performance. Thresholds can be easily calculated, if economic data and values for the relation between weed infestation and the losses are available.

Under German conditions in cereals and oil seed rape yield losses are focussed, while the other sources for economic losses depend almost exclusively on specific weed species, mainly *Galium aparine*. Therefore this species is handled very carefully in threshold concepts. However, the really occuring losses, caused by increased moisture content or decreased grain quality are variable and avoid numeric predictions (Wahmhoff & Heitefuss 1985, Gerowitt 1992, Werner & Heitefuss 1996).

Simple linear regressions between weed variables and yield losses analysed from series of experiments were used to calculate ranges in which economic thresholds vary. The lower limits were taken as guide values (Gerowitt & Heitefuss 1990a).

A strong variation of relationships between weed variables and yield appear in all datasets - interessting enough independent working groups in Germany decided in the early eighties to first reduce the values to a pragmatic concept and apply it to real situations, instead of investigating more deeply the relationships and ways to reduce the variation. (Niemann 1981, Wahmhoff & Heitefuss 1985). The work resulted in fix guide values for weed economic thresholds.The values should be respected in control decisions in order to defend economic losses caused by competition. A very low value for *G. aparine* ensures grain quality and harvesting performance (BARTELS *et al*. 1983).

The relationship between weed infestation and yield loss is most attractive to biological sciences. There are various approaches all over the world to improve our knowledge and understanding about this relationship. Some approaches followed in Germany are reflected here.

Fix guide values for economic thresholds hardly differentiate for various species. In order to improve that, important species were investigated in different experimental designs, ranking from micro plotsize (0.5 - 2 m²) to medium plotsize (10 -20 m²) (Gerowitt 1992, Pallut & Roder 1992, Thole & Heitefuss 1992). Totally not more than 10 species need to be considered separately, comparable ranges of values for predicting yield losses were obtained per species.

Considering the time of emergence is another way to improve the prediction of yield losses. Whenever weed cover is estimated or measured, the values are influenced by the time of emergence of the weeds relatively to the crop. Gerowitt & Heitefuss (1990a) took the relation of the growth stages of gras weeds and cereal crop to vary the yield loss prediction.

To include a variable for the competitive ability of the crop seems worthwile. Gerowitt & Heitefuss (1990a) correct the estimated yield loss by a factor considering the actual crop cover compared to an optimal one, which slightly modifies the final prediction. Gerhards *et al*. (1994) directly include the crop cover in the calculation of the economic threshold as a ratio of weed and crop cover with a strong influence on the resulting economic threshold.

The situation in oil seed rape is more complex: The decision about control is always taken before winter, far before the final manifestation of the competition. Depending on the crop development, weeds can be completely supressed or can cause serious damages. Fix thresholds were considered (Wahmhoff 1990b), but soon regarded to be too simple. Therefore a concept was step by step developed considering the competitive effects of important weed species (Kust *et al*. 1988), the relative time of emergence and the relation between crop and weed cover (Munzel *et al*. 1992). The resulting principles for a weed control can be either used as a calculation scheme (Munzel *et al*. 1991) or as a computer programme (Bodendorfer *et al*. 1994).

For weed research **in the developing world** numerous questions can be derived: Obtaining e.g. knowledge about the competitive effects of weeds, probably distinguished between important species, knowledge about the interference of weeds with quality and performance variables, an impression about the seed production of weeds in the actual crop. Besides the fact, that a stock of knowledge will be already availabel, the challenge is to follow the essential questions and to negociate a required level of accurancy regarding the usually short resources.

Constructing tools, as simple as possible, but defending the relevant damages caused by endured weeds, should be the general aim. German experiences indicate, that it is worthwile to collect the required knowledge in applied field research. There is no example, that the economic threshold work was definitly influenced by any greenhouse or CE experiment. Furthermore field experiments often offer possibilities to collect various type of data in the same approach. Besides classical randomized designs, simple approaches like strips in the fields may add relevant data.

IV. Consequences

<u>- in the actual crop:</u> Results of various experimental approaches (e.g. devided farmers fields, strip design, randomized design) indicate that small surviving weed infestations did not cause yield losses and, as long as a few species are handled carefully, did also not cause quality losses (Niemann 1981, Wahmhoff & Heitefuss 1985, Gerowitt & Heitefuss 1990a, Gerowitt 1992). The shift from fix guide values to variable decision systems gave some further improvement in economic net return by identifying cases with no need for control. Final economic evaluations indicate that in 20 - 50 % of the cases spraying was not necessary.

Improving average net returns does not guarantee, that all decision are ex-post correct. However, it became evident, that decisions based on economic thresholds offer more ex-ante security than prophylactic spraying (Gerowitt 1992, Wahmhoff 1990b).

Data from Gerowitt (1992) showed that compared to farmers control tactics economic thresholds increased the average net return by 44 DM/ha, while 41 % were not sprayed at all and the other were controlled selectively against gras weeds and/or *Galium aparine*. 86 % of the decisions were ex-post correct. The concept of Gerhards *et al.* (1994) checked on 80 farmers fields with winter wheat, winter barley and winter rye, lead to 73 % cases with no recommendation for control.

In oil seed rape the decision system for weed control according to economic thresholds was checked for yield effects in a series of randomized experiments (Munzel *et al*. 1992, Werner & Heitefuss 1996). Non-yield variables like moisture and grain quality were observed in strip designs on farmers fields (Werner & Heitefuss 1996). All investigations indicate, that control decisions according to economic thresholds with the decision scheme are as secure as in cereals. Less than 10 % wrong decisions were reported by Munzel *et al*. (1992) and Werner & Heitefuss (1996). Again, *Galium aparine* needs a special low threshold, in order to prevent the non-yield losses (Werner & Heitefuss 1996).

<u>in the following years</u>: In a simple approach, 1984-86 parts of farmers fields were treated according to economic thresholds (Wahmhoff 1990b). No weed control due to economic thresholds was applied in 31% of the fields, while in the residual cases control cost could be reduced by 47% due to selective spraying considering data of the field assessment. On fields carrying winter cereals the two years following the experiments, weed infestations tend to be slightly higher on the part with economic threshold use. In three of 35 cases higher cost of control of 76 DM/ha would have been occured, because the infestations required more control than in the part with conventional weed control (Wahmhoff 1990b).

Schulze-Lohne *et al*. (1996) observed five random design experiments during three years. Various weed control tactics were applied in cereals 1993, including a treatment with control according to the decision system of Gerehards *et al*. (1994). One case with higher densities of weeds appeared in the consecutive crops, which causes neither fundamental control problems nor any augmented herbicide dosage (Schulze-Lohne *et al*. 1996). Furthermore, initial field densities in 1993 already varied between the treatments - a fact stressing the importance to also look for the seed bank development in the long-term.

- in the long-term: Since 1981 a long-term experiment offers data about the development of actual infestations and seed banks in different control tactics in the crop rotation beet - winter wheat - winter barley (Heitefuss *et al.* 1994). One tactic is to consider weed economic thresholds (fix guide values) in winter wheat and winter barley. In the period of 15 years (1982 - 1996) gras weeds were not controlled 9 times in wheat and 7 times in barley. Control of *Galium aparine* was skipped only three times per cereal crop. In most years actual densities were smallest in the treatment with control in all crops. In the treatment ´Economic thresholds´ actual densities varied in a range, that still offers opportunities to skip control. Seed banks of annual grases are stabilized over the years in the treatment ´Economic threshold´ around the starting level. Intensive herbicide use lead to decreasing seed banks in the beginnings, which augmented again, if a species was favoured by annual conditions.

The general conclusion of this experiment, that small weed infestations in competitive crops do not lead to explosing seed banks, is not only important for weed economic thresholds, but for every tactic which may leave residual weeds in the crops, e.g. spraying reduced dosages or mechanical weed control.

Consequences with various time perspectives need to be regarded, if threshold concepts should be developed and transfered into praxis in the **developing world**. Questions about consequences are predestinated for integrating simple experiments by farmers themselves.

V. Acceptance

In Germany the argument, that weed control considering economic thresholds seems rational in cereals was taken up from all branches of advising business, like official advisory service, and advices of the chemical companies. Guide values for weed economic thresholds in cereals are mainly mentioned, while all appoaches to further develop the system (as reviewed in „Concept“) still have hardly any practical relevance. In all written information of the official plant protection service economic thresholds for weeds are mentioned. This „official“ part is strongly supported by having Integrated Pest Management as the legal base for pesticide use included in the German Plant Protection Act (PflSchG 1985, §6). Economic thresholds for weeds are handled as one of the cornerstones of IPM in arable systems in Germany.

Interviewing advisors of the German Plant Protection Service and farmers in the federal state Nordrhein-Westfalen indicated that they consider economic thresholds for weed control in around 12 %. However, when the farmers should indicate instruments to reduce herbicide use, 76 % declare, that economic thresholds are an important tool.

Which reasons could be responsible for any reservation against economic thresholds? Farmers often mention the possibilities to use reduced herbicide dosages. Dose response curves clearly indicate, that the younger the weeds are the smaller the dose can be. Despite a post-sowing application before weed emergence, data of experiments show, that economic thresholds are applicable even in very early growth stages, which offer possibilities to reduce the dosage, if control is required (Gerowitt 1992).

The concept of weed economic thresholds belongs to a farm structure, that guarantees time for spraying could be substituted by time for doing the weed assessments. That is realized on small to medium sized farms, where a well educated farmer is doing almost all work himself. Farmers and advicers often mentioned a sort of „security“ in their daily business after having sprayed or having recommeded spraying. The data presented here only inlcude experimental data, special „on farm“ conditions may further influence the decisions.

Considering economic thresholds is only one instrument in Integrated Weed Management. Reducing the actual infestation with strategical and tactical cropping practices is primarily important and second, if nessecary, using environment friendly control methods. In the long term weed species composition should be redeveloped to more diversity. In Germany, at least in scientific circles, also the beneficial aspects of residual weed infestations for self regulating processes in arable farming are more and more discussed (Gereowitt *et al.* 1996).

Besides the general conditions, individual farmers should take into account, wether an arable system is run, which is generally accompagnied by more weeds (e.g. crop monocultures, minimun tillage, organic agriculture). There, opportunities to skip weed control because thresholds are not exceeded are smaller.

Weed economic threshold work in the **developing world** has to adapt the level of the required information to the farmers. Top-down regulations cannot guarantee acceptance, especially when the activities are almost uncontrolable.

Conclusions

Economic thresholds can help to get a rational impression why weeds need control. Omit weed control in some cases, reduce costs of control and reduce herbicide input in the agroecosystem can be further obtained depending on the conditions. If only the first argument (rational impression) fits, resources are better spent in optimizing ways of control. So far, in situations, where efficient control is required because of actual or long-term losses, but cannot be achieved, weed research for thresholds offers knowledge for ranking the necessity of control.

Collaborating as close as possible with farmers offer various advantages: Monitoring weed species and weed control strengthen the interest of farmers and advisers for facts and problems. A concept not exclusively developed by scientists but including data of simple experimental approaches will support acceptance. Furthermore it guarantees a „living“ connection between weed science and farming practice.

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HERBICIDE USE AND TRANSGENIC CROPS RESISTANT TO HERBICIDES

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Summary

The tendency to use more herbicide in agriculture is intensifying all over the world including in the developing countries. The rapid growth in number and distribution of crop cultivars containing transgenes for herbicide resistance (HRC), poses a potential blessing to agriculture as well as a threat to the well being of the agro-ecosystem. The introduction of HRC into the farming system may facilitate the use of environmentally friendly herbicides and improve the cost-effectiveness and profitability of weed control. It may result in reduction in the damage caused to crop plants by misuse of herbicides and the need of manpower for hand weeding. It may also help overcoming parasitic weeds and herbicide-resistant weeds. However, too hastily adoption of HRC may result in irreversible damage to the agro-ecosystem, by increasing the dependence on chemical control methods and tempting the farmer to use higher rates and repeated applications of herbicides. This is trend emphasized with generic and cheap herbicides. Above all, the selection pressure on the weed population will increase and that will shift it toward higher infestation with troublesome weeds and faster evolution of herbicide-resistant weeds. There is also a risk gene transfer by cross-pollination from HRC to weeds resulting in the formation of 'super weed'. The problem of 'hard-to kill' 'volunteers' infesting the following crops in the rotation will also increase. Strict risk assessment and careful measures should be taken before any introduction of HRC into the farming system.

I. Introduction

Herbicides became an important component of agricultural production worldwide. Farmers rely more and more on chemical control, as manpower became less available, and mechanization, fertilization and improved seeds became the dominant technology (Nicholls & Altieri, 1997).

The recent commercialization of crop cultivars containing transgenes for herbicide resistance (HRC) in North America, Europe and in other parts of the world, poses a potential blessing to agriculture as well as potentail threat to the well being of the agro-ecosystem. Due to high commercial value of the HRC the number of releases all over the world will only increase in the near future and will certainly affect the market in the developing world as well. In OECD countries, nearly 1800 experimental releases of HRC were recorded until the end of 1996 (Cooper & Raybould, 1997). Until February 1997, 830 genetically modified (GM) plants releases were reported in the EU, primarily for research (Askew, 1997), however in the USA and Canada several HRC are registered, including glyphosate-resistant (Roundup Ready) soybean, canola and cotton, gluphosinate-resistant canola and corn, and imidazolinone resistant corn. Glyphosate-resistant soybeans have been introduced in 1997 to Argentina and suppose to be introduced during 1998 into the Brazilian agriculture as well. At present, field experiments with HRC are being conducted in different parts of the world including in developing countries (Berner *et al*, 1997). The combination of increase in chemical weed control together with the introduction of HRC will be discussed in this paper.

II. Trends in Herbicide Use

In 1996, herbicides market comprised more than 48% of the total pesticide market (US$ 31.125 billion), and on year 2001 expected to reach a peak of 49.2% of the total pesticide market (US$ 33.83 billion) (Phillips *et al*, 1997). Although the estimated proportion of the developing countries including East Asia (19.1%), East Europe (2.8%) and Latin America (9.4%) in herbicide sales is rather low (Jutsum and Graham, 1995), it is now in the middle of dramatic change. The changes in pesticide use in Latin America are of a particular interest as the expenditures for pesticides has more than doubled during one decade (1980 to 1990) (Nicholls and Altieri, 1997). The authors demonstrated that total US$ spent on pesticides in South America increased from US$ 1.0 billion in 1980 to US$ 2.7 billion in 1990. This increase in pesticide sales is a common tendency in all South American countries (Table 1), with the herbicides sales outweighing the market. This heavy reliance on pesticide can be found in the third world countries in big farms and much less in small-scale farming. Smallholder farmers in the developing countries do not always benefit from the increase in herbicide consumption, due to inadequate purchasing power to acquire the chemicals and the needed sprayers. Moreover, lack of knowledge and technology often leads to improper application of herbicides, health and environmental hazards, carry-over problems, crop damage and yield losses (Labrada & Parker, 1994).

Table 1. Expenditures on pesticides in Latin America
(Modified after Nicholls & Altieri, 1997).

	US$ Million	
Country	**1980**	**1990**
Argentina	102	241
Bolivia	9	18
Brazil	695	1973
Chile	8	17
Colombia	96	250
Ecuador	41	84
Guyana	6	12
Paraguay	2	5
Peru	14	30
Uruguay	7	18
Venezuela	22	61
Mexico	199	565

III. Potential Benefits of HRC

The introduction of HRC into the farming system may be beneficial, especially when the otherwise non-selective active ingredients such as glyphosate and glufosinate are used. The benefits are in yield, through improved weed control; in quality, through removal of existing volunteers of the same species; and in reduced cost of production by using rather cheap and non-selective herbicides (Askew, 1997).

It may also facilitate the use of environmentally friendly herbicides, prevent carry over and damage to non-target crops, hence further improving the cost-effectiveness and profitability of weed control. It may result in reduction in the damage caused to crop plants by misuse of herbicides and in certain crops - the need of manpower for hand weeding. The latter might be advantageous in the developed countries farming systems (Burnside, 1996), but much less so in the developing world, at least in the short term. In the long term, it might free the women and children to get discharged from the hand weeding tasks and exploit their time for favored and more beneficial activities.

IV. Potential Risks of HRC

However, too hastily adoption of HRC may result in irreversible damage to the agro-ecosystem. The use of HRC will increase the dependence on chemical control methods and may tempt the farmer to use higher rates and repeated applications of herbicides hence, further exacerbate the dependence on herbicides. This is particularly true when the herbicide is generic and cheap. The impact of this trend may affect the environment through ground- and surface water quality, herbicide drift and volatility, soil erosion and wildlife mortality. One should take into account that the rapid introduction of HRC may slower the process of promotion of IPM concepts into the weed management practices. On the other hand, using 'environmentally benign' broad-spectrum herbicide in HRC crops may facilitate the removal of 'harsh' herbicides from the market (Burnside, 1996), hence reducing the concern about using HRC .

Above all, repeated use of the same herbicide or herbicide with the same mode of action, will increase the selection pressure on the weed population and shift it toward the establishment of those species that are not easily controlled by the chemical (Rubin, 1996). In fact, the continuous use of glyphosate in orchards and fruit trees in Israel resulted in a significant increase in the infestation of weeds such as *Malva sylvestris*, *Convolvulus arvensis* and many legume weeds which are not easily controlled with this herbicide (Rubin. & Feterman, unpublished). The temptation to apply low-cost chemical at higher rates and repeatedly will further increase the selection pressure on the weed population, will eventually select for the very few resistant individual weeds present in the population. Given the intention to produce as many HRC as possible conferring the same resistance trait [e.g., 'Roundup-ready' soybean, cotton, corn, and canola (Welsh, 1995)] one can easily formulate a nice crop rotation repeatedly treated for several years with the same herbicide. Recently, in Australia, repeated application of glyphosate resulted in the evolution of a resistant weed biotype of *Lolium rigidum* that requires much higher rates for control (Sindel, 1996).

Similar scenario could be easily formulated for the more 'harsh' group of herbicides - the ALS inhibitors (sulfonylureas, imidazolinones and triazolopyrimidines). These highly effective broad-spectrum herbicide groups who share similar target site, are widely used in many rotational crops, grasses and broad-leaved as well as in monoculture. Resistance due to target-site and enhanced metabolism has quickly evolved in many weed populations all over the world (see reviews – Saari *et al.* 1994; Rubin, 1996). The fact that almost all weed populations that evolved resistance to a representative chemical of one group is, to some extent, cross-resistant to almost all herbicides from all three groups, makes any preventive management very complex and nonrealistic. The introduction of otherwise sensitive major HRC (*e.g.*, corn, rice and soybeans) to ALS inhibitors will certainly exacerbate the problem to a critic point of forcing sanctioned removal of rather important members of the group from the market. A possible use of ALS- or glyphosate- resistant crops for selective control of parasitic weeds, such as *Striga* spp (Berner *et al*, 1997) and *Orobanche* spp (Joel *et al*, 1995), with low doses of herbicides may open up a small window of hope to the developing world. One should be aware of the risks associated with this approach as parasitic weeds such as ALS-resistant *Cuscuta campestris* has been already reported (Sibony *et al*, 1997)

Most broad-leaved crops are naturally resistant to ACCase inhibitors from the aryloxy-phenoxypropanoates (AOPPs or 'fops') and cyclohexandiones (CHDs or 'dims') groups whereas annual and perennial grass weeds and crops are sensitive. The differential response between broad-leaves and grasses is based on the high sensitivity of grass ACCase to these herbicides as compared with the low sensitivity of the broad-leaves ACCase. Certain cereal crops are able to rapidly detoxify some fops and dims such as diclofop, fenoxaprop, clodinafop and tralkoxydim (Devine & Shimabukuro, 1994). Widespread and repeated use of selective fops and dims in cereal crops monoculture resulted in a rapid evolution of resistant grass weeds (See Devine, 1997 for recent review).

The high selectivity of these herbicides to broad leaved crops combined with the severe yield losses caused by the grass weeds, tempt the farmer to repeatedly use these herbicides as described in table 2 (Wiederholt & Stoltenberg, 1995). In spite of crop rotation and the incorporation of other herbicides in the weed management practice, the inevitable outcome was the evolution of crabgrass (*Digitaria sanguinalis*) biotype highly resistant to ACCase inhibitors.

This case albeit seems exceptional, may represent future scenarios in HRC as well. Another risk in the cultivation of HRC such as oil seed rape, lupins, wheat, sorghum, sugar beet and rice is th fear of gene transfer by cross pollination to the 'wild relatives' weeds resulting in the possibel formation of 'super weed'. There are numerous reports where different estimations were made for the distance the HRC pollen can travel and the chances for cross pollination with weeds to occur (Chevre *et al*, 1997; Darmency *et al*, 1995; Mikkelsen *et al,* 1996; Timmons *et al*, 1996). In spite of the preventive measures taken (e.g. male sterility of the HRC), crosses with weeds have been reported and they are boundto increase in frequency as the acreage and diversity of HRC increases. The author suggests to investigate the potential of 'gene silencing' that will abolish the resistance trait at certain age of the crop or at least before flowering, thus preventing the farmer from over-use of the herbicide as well as gene transfer by pollen. Although the risk is present and HRCs are grown for several years no disaster is reported. Claims are raised that the question of possible introgression between the HRC and relative weeds to form 'super-weeds' is probably exaggerated and the risk is much lower than the benefit (Sweet *et al*, 1997).

Another issue concerning HRC is how to deal with problems such as seed dispersal while transported from the field to storage or comsumption sites. The problem occurs not only in the country of production but also following export to and transport in other countries for processing or comsumption. 'Escapes' can drop to the roadsides where related wild weeds are grown and may cross with them or become 'volunteers' and spread. Herbicide-resistant 'volunteers' infesting the following crops in the rotation is crucial and distressing problem as it requires the use of additional measures to be controlled. Quite often these 'measures' are additional herbicide treatment which exhausts one of the benefits of HRC.

Conclusion

There is no doubt that HRC will increase in popularity and with a concomitant increase in the associated problems. The developed World is much better prepared to combat these difficulties with alternative technologies. However, in developing countries, particularly in smallholder farms, that should cope at once with adoption of several technologies (*e.g.* herbicide and HRC use), lack the capacity to overcome these difficulties. Hence, strict 'risk assessment' and careful measures should be taken before any introduction of HRC into their farming system.

Table 2. Crops and Herbicides used in muck soil field at Portage, Wisconsin where resistant crabgrass has evolved in 1992.

The number in parenthesis is the number of treatment/year (Modified after Wiederholt & Stoltenberg, 1995)

YEAR	**CROP**	**HERBICIDE**
1985	Onions	Bentazon, fluazifop, metolachlor, oxyufluorfen(2), sethoxydim(2).
1986	Corn	Alachlor, bentazon.
1987	Carrots	Fluazifop, linuron (4), metribuzin
1988	Onions	Bentazon, bromoxynil, fluazifop(5) metolachlor(2), oxyfluorfen(4).
1989	Carrots	Fluazifop(2), linuron(4), metribuzin
1990	Onions	Fluazifop(4), oxyfluorfen(4), pendimethalin(2).
1991	Corn	Atrazine, bentazon, dicamba, pendimethalin.
1992	Onions	Fluazifop(3), oxyfluorfen(4), pendimethalin(3), sethoxydim(3).

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SYSTEMS APPROACHES IN WEED MANAGEMENT AND THE DESIGN OF WEED SUPPRESSING CROP VARIETIES

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Summary

The development of sustainable agricultural production systems demands weed management with a reduced dependency on herbicides. This can only be realised if suitable alternative weed management options, be it preventive measures or curative weed control techniques, are available. Insight in processes related to crop-weed interactions and weed population dynamics might help in the development of preventive measures and to identify new opportunities for weed control.

Furthermore this insight can be used to improve operational and tactical decision making and to design and explore long-term strategies for weed management. The complexity of the processes involved in crop-weed interactions and the long-term character of weed population dynamics hints at the use of simulation models. In this paper the state of the art of weed-crop ecophysiological knowledge is briefly described and its contribution to the development of sustainable agricultural production systems by improving present-day weed management systems is discussed. The development of weed suppressing varieties of crops may be one of the options for preventive weed management. Insight in processes related to crop-weed interactions and weed population dynamics might help in the development of such preventive measures. This paper explores the opportunities of using systems approaches and models to design weed suppressing varieties without trade offs with yield.

The suitability of a mechanistic simulation model (INTERCOM) for crop-weed interaction for this purpose was determined in a combined modeling and experimental study, where large differences in competitive ability between rice cultivars were analysed. The analysis revealed that competitive ability was mainly related to relative leaf area growth rate early in the season and larger maximum plant height. Because factors such as lodging are not simulated by the model, its use for design of more competitive rice cultivars will require continuous interaction between modelling and experimentation. In another study competitive ability of sugar beet was studies and large effects of leaf angle distribution were found.

The model was used to quantify the potential contribution of various attributes to competitive ability. A sensitivity analysis demonstrated that competition for light is mainly determined by morphological characteristics of which early relative leaf area growth rate, early relative height growth rate and maximum plant height were found to be the most important. The ability of the model to identify key traits with respect to competitive ability makes it a useful tool for designing ideotypes. The systems approach provides guidelines for the design of weed suppressing varieties with minimum trade offs with yield. An approach to use (colored varieties of) different crops as model weeds to evaluate the weed suppressing ability in breeding programs.

1. Introduction

In most agricultural systems, weed management has been one of the major issues determining the design of cropping systems, especially in the absense of herbicides. The use and application of herbicides was one of the main factors enabling intensification of agriculture in developed countries in the past decades. More recently, the availability of herbicides has been coupled to intensification of agriculture in developing countries as well. A well-described example is the recent area expansion of direct seeded rice in Asian countries; a technology not widely practised before the late seventies largely because of weed control problems and now becoming a major system in Asian tiger economies, like Malaysia and Korea, where labour shortage is pressing.

Selection of genotypes with an improved competitive ability can be done in two ways (Lemerle et al., 1996). One involves direct selection of genotypes grown in the presence of weeds. Useful selection criteria in this approach are absolute grain yield under weed-free conditions, relative grain yield in the presence of weeds, and weed biomass. Direct selection with real competition is only possible, however, in the later stages of a breeding program when sufficient seed is available. Furthermore, experimental analysis of the competitive ability of a wide range of genotypes is very labour intensive and expensive (Wall, 1983).

An alternative approach is indirect selection in which selection is aimed at attributes, such as plant height, that are associated with competitive ability. Selection can thus be started early in the breeding program and can be carried out in the absence of weeds. Traits contributing to competitive ability need to be identified prior to the actual selection, however. Mechanistic crop growth models have proven to be valuable tools for ideotype design, as was demonstrated recently with the design of a high-yielding plant type for irrigated rice ecosystems (Dingkuhn et al., 1991; Penning de Vries, 1991; Kropff et al., 1994). Similarly, mechanistic competition models have the potential to identify key traits with respect to competitive ability, and should therefore be useful tools for designing more competitive rice cultivars. A mechanistic model of competition between sugarbeet (*Beta vulgaris*) and *Chenopodium album* has, in fact, been used to select sugarbeet cultivars with increased competitiveness due to early ground cover (Lotz et al., 1991).

In this paper we explore the opportunities to use systems approaches and ecophysiological competition models such as INTERCOM to explain differences in competitiveness between cultivars, and subsequently to identify the major attributes with respect to competitive ability. The analysis is used to exemplify usefulness and limitations of ecophysiological competition models in designing more competitive cultivars. This paper is largely based on Kropff and van Laar (1993), Bastiaans et al. (1997) and Lotz et al (1991).

2. The model INTERCOM

Competition is a dynamic process that can be understood from the distribution of the growth-determining (light) or -limiting (water and nutrients) resources over the competing species and the efficiency with which each species uses the resources. Eco-physiological models that simulate the physiological, morphological and phenological processes provide insight into competition effects observed in (field) experiments and can help in seeking ways to manipulate competitive relations, such as those between crop and weeds by determining the most important factors in crop-weed competition.

Various competition models have been developed (Spitters & Aerts 1983, Kropff *et al.* 1984, Graf *et al.* 1990, Wilkerson *et al.* 1990, Kropff & Van Laar 1993). The eco-physiological model INTERCOM described by Kropff & Van Laar (1993) consists of a number of coupled crop growth models equal to the number of competing species and is based on the early versions of Spitters and Aerts (1983) and Kropff et al. (1984). A detailed description of the model was given by Kropff and van Laar (1993.

The ecophysiological model INTERCOM described by Kropff and Van Laar (1993) consists of a set of individual growth models (one for each competing species), that calculate the rates of growth and development for species based on environmental conditions. The growth models are expanded to account for morphological processes that only affect growth in competition and coupled to account for the simultaneous absorption of available resources by the different species in a mixed vegetation. Under favourable conditions, light is the main factor determining the growth rate of the crop and its associated weeds. In INTERCOM, the quantity of photosynthetically active radiation absorbed in mixed canopies by each species is a function of the amount and vertical distribution of photosynthetic area within the canopy, and the light extinction coefficient of the species. A water balance for a free draining soil profile is attached to the model, tracking the available amount of soil moisture during the growing season. When available soil moisture drops below a critical level, transpiration and growth rates of each species are reduced. Since transpiration is driven by the absorbed amount of radiation and the vapour pressure deficit inside the canopy, competition for water is closely linked to aboveground competition for light. The more light a species absorbs, the more water is required for transpiration. Direct competition for water as a result of differences in rooting density is not accounted for. An extension of the model for simulation of competition for nitrogen has been described, but has not yet been implemented.

The eco-physiological competition model has been tested with data from competition experiments with several data sets: maize (*Zea mays* L.), yellow mustard (*Sinapis arvensis* L.) and barnyard grass (*Echinochloa crus-galli* L.) in the Netherlands (Kropff *et al.* 1984, Spitters 1984, Spitters & Aerts 1983, Weaver *et al.* 1992), tomato (*Lycopersicon esculentum* L.)-pigweed (*Amaranthus retroflexus* L.), tomato-eastern black nightshade (*S. americana*) (Weaver *et al.* 1987) in Canada (Kropff *et al.* 1992), and rice and *E. crus-galli* in the Philippines (Kropff & Van Laar 1993).

The results of these studies indicate that interplant competition for light and water can be explained on basis of the underlying physiological processes. The main gaps in knowledge are related to morphological development and especially the phenotypic plasticity of weeds with respect to these morphological features such as height development, leaf area development.

Applications of these models can be found in the development of new simple predictive models for yield loss due to weeds, the analysis and extrapolation of experimental data, the analysis of the impact of sub-lethal control measures (like low-dosages of herbicides), the design of new competitive crop-plant types for weed suppression and risk analysis for the development of weed management strategies.

The ecophysiological model INTERCOM (Kropff and van Laar, 1993) was used to analyse differences in competitive ability between IR8 and Mahsuri (Bastiaans et al., 1997) and differences between several sugar beet cultivars by Lotz et al. (1991; 1995).

In this paper only a brief description of the routines for relating genotypic differences in phenological, physiological and morphological attributes to differences in competitive ability are given.

In INTERCOM, phenological development rate of a species is tracked as a function of daily average of the ambient temperature. A separate development rate is used for the period from emergence to flowering (DVR_{veg}; (°C d)$^{-1}$), and the period from flowering to maturity (DVR_{rep}; (°C d)$^{-1}$).

Daily gross assimilation rate of a species is based upon the profile of absorbed photosynthetically active radiation (PAR) in the canopy and the photosynthesis light-response curve of individual leaves. After subtracting respiration requirements for maintenance, the net daily growth rate is obtained using a conversion factor for the transformation of carbohydrates into structural dry matter. The dry matter produced is partitioned to leaves, stems, roots and panicles using empirical partitioning functions. Integration of the daily growth rates of the organs results in the time course of accumulated dry weight.

The way in which the expansion of leaf area index (LAI) is simulated depends on the absolute leaf area index. Early in the season, until the total canopy has reached a leaf area index of 1.0, leaf area development is simulated on the basis of an experimentally determined temperature-dependent relative growth rate of leaf area:
RGR_{la} = relative leaf area growth rate ((°C d)$^{-1}$). Following this early growth period, the increase in LAI is obtained from the increase in leaf weight using specific leaf area (SLA; m^2 leaf (kg leaf)$^{-1}$). Plant height (H(ts)) is simulated with a Gompertz function where H_b and H_c are coefficients defining the shape of the function and H_{max}, the maximum height of the species (m), operates as a scaling factor. Early height growth is greatly affected by H_c.

3. Analysis of competitive ability and yielding ability in rice

3.1 Experimental

The competitive ability rice cultivars was measured in field experiments conducted in the dry season of 1993 at the International Rice Research Institute (IRRI), Los Baños, Philippines. Four rice cultivars (IR8, IR50, Mahsuri and Oryzica llanos 5) were grown in monoculture and in mixture with two densities of purple rice. Purple rice (*O. sativa*) is an IRRI bred cultivar, that is being used at IRRI as a boundary marker in Plant Breeding experiments. In this experiment purple rice was used as a model weed because it is easy distinguishable from ordinary rice and because its maximum height is comparable to that of *Echinochloa crus-galli*, the main weed species in rice. Furthermore, purple rice enables the establishment of a homogenous weed-stand by mixing its seed to the seed of the concerning cultivars. The cultivars with the lowest and the highest competitive ability were IR8 and Mahsuri, respectively. Mashuri is a native cultivar that originates from Malaysia. It is a tall growing cultivar, with fast growth at early stages. IR8 is the first IRRI-bred semi-dwarf high yielding cultivar. For a detailed description of this study we refer to Bastiaans et al. (1997).

In monoculture, shoot biomass of Mahsuri was clearly greater than shoot biomass of IR8 (Figure 1a). The response of the cultivars in terms of grain yield was exactly opposite (Figure 1b). The small harvest index of Mahsuri was associated with a longer vegetative period, a larger fraction unproductive tillers (28% compared to 7% for IR8) and lodging of this tall-growing variety during grain filling. Competitive ability of Mahsuri was greater than that of IR8. Shoot dry weight of Mahsuri was hardly affected by the presence of purple rice, whereas shoot dry weight of IR8 was severely reduced at both densities. For both cultivars, reduction in grain yield surpassed reduction in shoot biomass. The greater weed-suppressing ability of Mahsuri was confirmed by observations on the weed. Total shoot biomass and plant density of purple rice in mixture with Mahsuri were both less than in mixture with IR8.

Fig. 1. Observed shoot biomass (kg ha^{-1}) (A) and grain yield (ka ha^{-1}) (B) of rice cultivars IR8 (dotted) and Mahsuri (shaded) in monoculture and in mixture with purple rice.

Table 1
Phenological, physiological and morphological characterisation of IR8, Mahsuri and purple rice. For an explanation of parameters see text. After Bastiaans et al. (1997).

	IR8	Mahsuri	purple rice
Phenology			
Vegetative phase			
- duration (d)	81	97	76
- DVR_{veg} ((°C d)$^{-1}$)	0.00066	0.00054	0.00071
Reproductive phase			
- duration (d)	31	29	32
- DVR_{rep} ((°C d)$^{-1}$)	0.00154	0.00160	0.00149
Physiology			
- Growth rate (kg ha^{-1}d^{-1})	125	159	85
Morphology			
- LAI(0)	0.0050	0.0035	0.0051
- RGR_{la} ((°C d)$^{-1}$)	0.0135	0.0182	0.0139
- SLA (m^2 kg^{-1})	26	21	24
- H_{max} (m)	0.72	1.24	1.11
- H_c ((°C d)$^{-1}$)	0.00271	0.00282	0.00242

3.2 Cultivar characterisation
Phenological, physiological and morphological traits of IR8, Mahsuri and purple rice were quantified based on the observations in the monoculture plots. The traits were expressed as parameters for INTERCOM (Table 1). Considerable differences were observed. IR8 is medium-maturing, whereas Mahsuri is long-maturing. Differences in the rate of phenological development occurred mainly in the vegetative phase. Growth rate of IR8 and Mahsuri in the linear growth phase, as determined between 34 and 98 DAS, differed considerably. The growth rate of Mahsuri was about 20% greater than that of IR8. Differences in the distribution of accumulated dry weight over the various shoot organs developed mainly in the latter part of the growing season. The partitioning patterns of both cultivars were basically the same, differing only in the time at which the panicle became a major sink. Relative leaf area growth rate (RGR_{la}) of Mahsuri was 35% higher than of IR8. Throughout the growing season, IR8 produced slightly thinner leaves than Mahsuri. The difference in SLA as presented in Table 1 represents the difference in the second half of the growing season. In the first part of the growing season, SLA of both cultivars was larger, but the relative difference was nearly the same. Maximum plant height of IR8 was over 40% shorter than of the tall-growing Mahsuri. Differences in relative height growth rate (H_c) were only marginal. Maximum plant height and relative height growth rate together determine the actual difference in height growth rate.

3.3. Model analysis
After introduction of the experimentally determined phenological, physiological and morphological parameters in INTERCOM, the observed time course of dry weight in monocultures was used to calibrate the model for the two cultivars. Calibration was required to account for the differences in their crop growth rates. For IR8, calibration resulted in a good agreement between observed and simulated dry weight (Fig. 2). For Mahsuri a good agreement was obtained from emergence to flowering. After flowering, lodging occurred,

accompanied with a considerable reduction in crop growth rate. The model was not able to account for this sharp decline in crop growth rate. Simulated crop growth rate after flowering was about twice as high as the observed crop growth rate.

After calibration, the model was used to simulate dry matter production of both cultivars in competition with purple rice. The simulations resulted in an accurate simulation of competitive ability of both cultivars (Fig. 2). Dry matter production of IR8 was severely affected in competition with purple rice, whereas Mahsuri was found to be far more competitive. This result implies that the observed differences in phenological, physiological and morphological attributes of IR8 and Mahsuri would explain the differences in their competitive ability. The model was then used to identify which attributes were responsible for the differences.

Fig. 2 Simulated yield of IR8 isolines with different traits from Mahsuri in monoculture and in mixture.

Figure 3. Sensitivity of simulated yield reduction to changes in model input parameters. Yield reduction of IR8 was simulated in competition with purple rice (seeding rate: 30 kg ha^{-1}).

Relative sensitivity was calculated as the ratio of percentage change in the reduction in grain yield (or weed shoot biomass) and percentage change in input parameter. Relative sensitivity was based on results of runs with standard parameter values and a 10% increase in parameter values.

3.4 IR8 isolines

A comparison of the simulated yield reductions of IR8 and its hypothetical isolines indicate that maximum plant height and relative leaf area growth rate accounted for most of the differences (Figure 2). Isolines of IR8 improved in these two aspects suffered less yield reduction and suppressed weeds better than the other isolines. An enhanced growth rate was also found to increase competitive ability. More important in this case, however, was a general increase in grain yield. A prolonged vegetative growth also gave an apparent increase in competitive ability. The smaller simulated yield reduction in that case did not result from an improved weed suppressing ability, however, as simulated weed shoot weight increased slightly. A more detailed analysis of this model outcome revealed that prolonged vegetative growth increased the amount of vegetative biomass and consequently the respirative demand during grain filling. This lowered the rate of grain filling, causing a smaller harvest index. In competition, dry matter production in the vegetative phase was reduced and that led to a more efficient production during grain filling. The smaller respirative demand in competition thus partially compensated for adverse effects due to the presence of purple rice, resulting in a pseudo-increase in competitive ability. The marginal differences in relative height growth rate hardly affected competitive ability, whereas the lower specific leaf area of Mahsuri had a slightly negative effect.

3.5 Sensitivity analyses

The differences in competitiveness among IR8 and its isolines were determined not only by the importance of a specific trait for competitive ability but also by genotypic variation between IR8 and Mahsuri for this trait. To determine the potential of various traits for competitive ability, irrespective of casual differences between IR8 and Mahsuri, sensitivity analyses were conducted. The results demonstrate that differences in phenological development rate do not affect weed suppressing ability (Figure 3). An increased growth rate resulted in a greater yield and, apart from that, in an increased competitive ability. Simulated yield loss was most sensitive to morphological characteristics. Parameter RGR_{la}, which determines the rate of leaf area development in early growth phases, was the most important factor. Plant height, which determines the vertical distribution of leaf area in the canopy, was also important. Simulated yield loss was very sensitive to both maximum plant height (H_{max}) and parameter H_c, which determines the earliness of height development. Specific leaf area (SLA) and the extinction coefficient during the later part of the growing season (k_{late}) had equal but less pronounced effects on simulated yield loss. Interestingly, their effect on grain yield in weed-free conditions was completely opposite. A 10 % increase in light extinction coefficient decreased simulated grain yield about 140 kg ha^{-1}. A higher light extinction coefficient resulted in a poor light penetration and poor distribution of radiation within the canopy, thereby reducing radiation-use efficiency. On the other hand, a 10% increase in SLA led to a simulated yield increase of close to 90 kg ha^{-1}. Thinner leaves resulted in earlier canopy closure and accordingly in an increase in grain yield.

4. sugarbeet-C album

The model INTERCOM was extensively evaluated for sugar beet-Chenopodium album competition (Kropff and van Laar, 1993). The relative sensitivity of sugarbeet yield loss as a function of varietal traits was determined in a simulation study and expressed as the ratio of % change in yield loss and % change in the value of the specific parameter.

Simulated yield loss was most sensitive to the morphological parameter RGR_{la}, which determines the rate of leaf area development in early growth phases in dependence of temperature, and the parameter H_c, which determines the earliness of height development in all competition situations. Simulated yield loss was less sensitive to physiological species characteristics (parameters related to photosynthesis) than to morphological parameters (parameters determining leaf area development, plant height and efficiency of light absorption). These results indicate the importance of accurate measurements of these parameters for prediction of the effects. On the other hand a strong sensitivity indicates large opportunities for breeders to develop varieties with a higher competitive ability. These results demonstrate the non-linear and strongly interrelated relationships between plant traits and their impact on competitive ability. The simulated results demonstrate that the sensitivity of yield loss (slope of the curves) to the relative maximum height of the weeds and its timing depends upon the relative maximum height of the weeds itself but also on weed density and the period between crop and weed emergence. These complex interrelationships indicate that experimental evaluation of the importance of such factors is extremely difficult. The most important trait determining competitive ability was the relative growth rate of the leaf area early in the season (Fig. 9.4), which has to be measured on isolated plants. Spitters and Kramer (1986) measured the relative growth rate of different wheat cultivars (on dry matter basis) and found a very small coefficient of variation (5%; values ranges from 0.178 - 2.040). They estimated from literature data that the coefficient of variation would range from 3 - 10%. Such a variation would lead to considerable differences in yield loss.

An eco-physiological model can be helpful in integrating the effects of these traits. Lotz *et al.* (1991) applied the model to select sugar beet cultivars with a relative high competitiveness due to early ground cover. They experimentally confirmed strong differences in survival of late emerging weeds between varieties (Table 2).

Table 2. Survival of Survival of C. album, S. media and P. persicaria seedlings (%) in sugarbeet varieties differing in leaf angle distribution at 2 locations in 2 years.

Cultivar	Droevendaal		De Eest	
	1989	1990	1990	
Lucy <Horizontal>	40	58	57	
Carla	54	70	66	<Medium>
Univers <Vertical>	64	72	77	

5. Discussion

The model analysis, based on quantification of phenological, physiological and morphological attributes of the rice varieties IR8 and Mahsuri, demonstrated that differences in competitive ability between the two cultivars are mainly due to differences in maximum plant height (H_{max}) and early leaf area growth rate (RGR_{la}). Sensitivity analyses confirmed that in situations were competition is mainly for light, the competitive ability of a species is determined primarily by morphological attributes. Similar conclusions were drawn by for example, Rooney (1991; wheat competing with *Avena fatua*) and Kropff et al. (1992; sugarbeet competing with *Chenopodium album*). This result clearly illustrates the role of simulation models for plant breeding; the models enable a quantitative estimation of potential contributions of various traits to an increased competitive ability, whereas the available genetic variation determines how much of this potential may be realised (Spitters and Aerts, 1983).

In the present analysis, the contribution of individual traits to competitive ability against weeds was estimated through the construction of hypothetical isolines. The model permitted construction of an unlimited number of isolines, by just changing the value of single parameters. Although this procedure is an appropriate way to estimate the importance of individual attributes, the created isolines do not necessarily represent realistic genotypes. In reality, the range of change of a single trait is restricted and determined by the available genetic variation. The feasibility of a separate change of a single trait is determined by the presence or absence of genetic and physical links with other traits. A close genetic linkage of traits will hamper the independent change of a single trait, whereas a physical linkage of traits prevents an independent change. Models, characterised as simplified representations of reality, never contain all existing physical links among traits simply because not all links are either known or properly understood. In the present analysis, for example, a calibration factor was introduced to account for differences in crop growth rate. Crop growth rate is thus to some extent simulated in a descriptive way, thereby neglecting its interference with other attributes. As a result, the model, apart from simulating the main effect of an attribute, might not always fully account for side effects. This incompleteness of the model with respect to interactions among traits should be kept in mind when interpreting outcomes of the model: rather than providing a detailed blueprint, the model is able only to construct a rough outline of a more competitive variety.

Sensitivity of simulated yield loss to early leaf area growth rate and early height growth rate underlines, for situations where competition is mainly for light, that the outcome of competitive relationships is to a large extent determined early in the season. This result is in line with the observation that the period between crop and weed emergence is a major determinant of yield reduction (Kropff et al., 1984). During early growth stages, a strong positive feedback exists between crop growth, leaf area formation and radiation interception (Blackman, 1919), through which small initial differences between crop and weed might soon be enlarged. For this reason, many weed management practices are directed towards improving the relative starting position of the crop compared to that of weeds.

Determination of relative leaf area and height growth rate requires repeated measurements early in the growing season. In a breeding program, where large numbers of genetic lines must be evaluated, such a time-consuming measurement protocol might not be feasible. This implies, for successful implementation in a breeding program, that some of the explanatory output of the model should be replaced by output that relates to practical screens that can be used by breeders. Thus, some initial model parameters used to explain differences in competitive ability among genetic lines, might be replaced by easily measured indicators of competitive ability. The present model can be used in designing simple screens. For a clustered parameter, such as RGR_{la}, one of the underlying components (e.g. tillering rate, leaf expansion rate or vertical leaf arrangement) might lead to a more practical measure of early leaf area growth rate. A more detailed model analysis can help to indicate the most promising component. Likewise, if relative height growth rate were to be replaced by a single measure of plant height, the model could be used to indicate the most suitable growth stage for measuring height.

Competitive ability of rice has often been reported to be negatively correlated with yield potential (Jennings and Aquino, 1968; Moody and De Datta, 1982). The results presented in this paper confirm that finding. In weed-free conditions, Mahsuri, being the cultivar with the highest competitive ability, was lower yielding than IR8. The ability of the model to estimate the contribution of individual traits to competitive ability can also be applied to rice productivity. In this way the trade-off between yielding ability and competitive ability can be determined for single traits. This procedure is illustrated clearly by a comparison of the effects of specific leaf area (SLA) and light extinction coefficient (k_{late}). An increase in either of these attributes leads to an identical increase in competitive ability, whereas the response of simulated grain yield in weed-free conditions to these changes is completely divergent. Simulated grain yield in weed-free conditions decreased with the larger light extinction coefficient (circa 140 kg ha^{-1}), whereas increased SLA resulted in a yield increase (circa 90 kg ha^{-1}). This example demonstrates that in principal the model was able to quantify trade-offs between competitive and yielding ability of single traits. On the other hand, there are situations where the model would not be able to quantify trade-offs. In the experiment, lodging of the tall-growing Mahsuri was observed after flowering, and this most likely contributed to the poor growth rate of the cultivar during kernel filling. Lodging (or the risk of lodging), associated with plant height, is not accounted for by the model. Similarly, the large fraction of unproductive tillers of Mahsuri in the experiment was not considered. In reality, unproductive tillers might operate as a weed and reduce the amount of radiation intercepted by the productive part of the crop. Because the model was developed for cultivars with few unproductive tillers, this aspect was neglected. For high-tillering cultivars, however, this simplification might not be justified. Because an increased rate of tillering might be one of the components that underlay an improved early leaf area growth rate, the trade-off of this attribute might well be underestimated. Both examples demonstrate that a full quantitative estimation of trade-off with the model is not yet feasible.

In the present analysis it was assumed that plants competed only for light. Competitive relationships are likely to be changed in situations where, apart from light, other resources are limiting growth. Traits that contribute to an improved competitive ability in a situation with ample water and nutrients might be less effective, ineffective or even detrimental in less favourable situations. The complexity of production situations requires a good quantitative understanding of the response of crop and weed to resource limitations before design-driven breeding programs can be initiated. The complexity and variability often encountered in cropping systems offer an enormous opportunity for mechanistic models of crop-weed interaction to contribute to the development of more competitive cultivars.

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BASIC ELEMENTS FOR IMPROVED WEED MANAGEMENT IN THE DEVELOPING WORLD

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SUMMARY

The agriculture of a majority of farmers in developing countries is at the low input level of production because the resource base of these farmers is low. Weed control is generally manual and involves the use of simple tools with the energy for weed removal coming primarily from humans but occasionally from animals drawing simple tools. Basic elements for improved weed management include an understanding of the bio-physical and socio-economical factors that affect smallholder agriculture; development of appropriate technologies that will minimize drudgery, make farming attractive, reduce soil degradation, and make it possible to grow crops on a sustainable yield basis. These elements also include the presence of a critical mass of resource persons to develop improved weed management technologies and transfer them to farmers.

I. INTRODUCTION

Low input agriculture is a common feature of food production in a cross-section of the developing countries of the world. Therefore any discussion on improving weed management practices used by farmers in these countries must take the resource base of these farmers into consideration. Because land holding is small and the resource base of farmers is low, appropriate weed control technologies that can be cost effective in low input farming systems are hard to come by. Very few weed management technologies have been developed to overcome drudgery associated with food production at the small input farmer level in the developing countries.

According to the Food and Agriculture Organization (FAO, 1995), the world currently has 137 countries grouped as developing countries and they include 72 that are known as low-income food-deficit countries. While 72% of all developing countries are located in Africa and Latin America, 60% of the low-income food-deficit countries are in Africa. These statistics should guide us in prioritizing our tasks of developing improved weed management technologies that will contribute to increased food production in the developing countries of the world. The need for appropriate weed management practices for developing countries has for many years been a constant concern for weed scientists in many parts of the world. The FAO in 1982 organized an expert consultation specifically on how to improve weed management in developing countries (FAO, 1984).

This organization has since taken other initiatives to move weed management forward in developing countries but these efforts have not borne the expected results. A recent review of the status of weed management technologies in developing countries of the world show that these countries in Africa and Latin America are further behind their counterparts in the rest of the world with respect to use of improved weed management technologies (Labrada, 1996). Low input farming systems of smallholder farmers in developing countries with their mixed cropping systems and high weed infestation, provide a challenge to weed control and to process level studies on weed biology and ecology. Knowledge of tropical weeds in food production systems of most developing countries is poor. There is very little progress that can be made in the development of improved weed management technologies until there is better knowledge of tropical weeds by farmers and researchers alike. The objective of this paper is to review basic elements of improved weed management in the developing countries in relation to the constraints to transfer and adoption of these technologies by farmers.

II. Integrated Weed Management in the Developing countries

Integrated weed management in developing countries has been reviewed recently (Akobundu, 1996a). A little earlier, Labrada *et al.* (1994) reviewed a similar subject with particular emphasis on the role of FAO in promoting improved weed management in the developing countries. According to a recent survey of the status of weed management in developing countries, only four countries have attained a high standard of weed management in Asia (Labrada, 1996). Lack of well-trained weed scientists and limited funding for research and extension were listed as the major constraints to poor development of weed management in the developing countries. Any initiative to increase food production in the developing countries through improvement in current weed management practices must include an investment in having well-trained weed scientists and ensuring that there will be funding for research and extension. In spite of the attention that has been given to weeds and their control in the tropics, no major breakthrough in methods of weed control at the smallholder farmer level has really occurred. Hand weeding and use of animal-drawn simple tools still dominate the agriculture of low input farmers of developing countries. The average farmer in a developing country has little or no resources and therefore can neither afford to take big risks nor go for technologies that require a lot of external inputs. A proper assessment of the prospects for improved weed management in low input farming systems should take stock of where farming in these countries has come from, where it is now, and where it is going.

III. Basic Elements for Improved Weed Management in the Developing World

Improved weed management in the developing world refers to technologies that can increase the farmer’s productivity, improve his/her welfare, and minimize drudgery associated with weed control. Development of improved weed management technologies requires that factors affecting weed biology and ecology, weed control, the biophysical environments associated with crop production, and the socio-economic circumstances of the farmer should be taken into consideration during technology development processes. In addition, improved weed management technologies have to be field-tested, and shown to be economical at scales comparable to those in which farmers, for whom the technologies are developed, will use them. In spite of what has been said or written to date, hardly any improved method of weed control has been packaged and field-tested to meet the special needs of smallholder farmers in most of the developing countries. Table 1 summarizes the features of past and present production environment of smallholder farmers in most developing countries.

There are indications that many traditional and low input production systems have cologically sound basis for their use by farmers. For example, mixed cropping systems that were in the past considered primitive have now been seen as having merits and built-in risk aversion techniques. They have also been recognized as appropriate for smallholder farming in the tropics where levels of inputs are low. In many instances where scientists have had the patience to understand the principles on which these smallholder farmers base their practices, these production practices have been seen to provide important conceptual framework for small scale production systems.

Table 1. Features of selected low input farming in developing countries[1]

Parameters	Past	Present
Household population	Large: many wives and children.	Large: one wife +≥ 5
Dwelling place	Mud house with thatched roof needing replacement every two years.	A few mud houses, cement block walls and with corrugated zinc roofs.
Garden plots and compound farms	Permanent cultivation with vegetables and economic tree crops.	Small gardens overcrowded with multi-storey crop.
Outlying arable fields	Arable crops: cultivation alternating with long fallow period >7 years.	Arable crops: continuous cropping or short duration bush fallow period of <2 years.
Demography	Large hectare/farmer ratio (>1.5).	Small hectare/farmer ratio (<1.0).
Crop yield	Adequate to meet family needs.	Inadequate to meet family needs.
Sustainability	Sustainable.	Not sustainable.
Weed problems	Mild to moderate.	Severe.
Weed type	Mostly annual broadleaf weeds.	Perennial weeds especially grasses, sedges and parasitic weeds.
Type of inputs	High for land clearing and low for weeding.	Low for land clearing but high for weeding.

Akobundu, 1966a.

Low input agriculture needs to maintain productivity at such high level as to make up for the limited cash flow capacity of farmers, and for the high human population that these low input systems are now forced to support. One conspicuous feature of the pressure on land is an increased land use intensity with its attendant high weed pressure. Farmers in these systems, particularly those associated with areas with high human population densities, lack the capacity to deal with the high of weed seed rain that follows crop harvest and the short fallow period with its attendant soil degradation.

Improved knowledge-base of weeds in the agriculture of developing countries.

Zimdahl (1994) defined weed science simply as the science of vegetation management. This is very true of the agriculture of developing countries. Weeds play more direct roles in the affairs of humans in developing countries than can be perceived and comprehended in developed countries. This subject has already been reviewed (Akobundu, 1991). Improved knowledge-base of weeds include weed identification, weed biology and ecology. For example, the periodicity of weed seed germination and the effect of land use systems on weed seed rain are poorly understood. This knowledge base is fundamental to the development of improved weed management technologies. In order for weed management practices that are developed for low input agriculture to have have universal appeal, they should at least be based on principles that have wide application. Examples of these principles are those that exploit the allelochemical properties of crop plants as has been reported for rice (Olofsdotter and Navarez, 1996.); biocontrol of weeds (Jimenez, 1996); and the potential use of mycoherbicides (Auld, 1994; O'Connell and Zoschke, 1996). Habitat management, as a tool in weed control, involves the modification of the micro environment shared by weeds and crops to favour the crop and discourage weed seed germination, weed seedling establishment, weed growth, and weed seed production. This weed management strategy has already been reported as effective in reducing a build-up of weed population. It has also been shown to be appropriate for sustainable food production in low-input farming systems (Akobundu, 1992). It is rare to see weed scientists in developing countries working on the biology and ecology of weeds.

Appropriate weed management technologies for the developing world.

Many developing countries appear to conjure images of desperation and stagnation. Smallholder farmers have for centuries been hand weeding with simple tools or using animal-drawn implements to contain weed problems in their fields. These farmers have also been yearning for alternatives to these basic weeding tools and methods. The biggest challenge facing weed scientists that work in developing is that of developing weed management strategies that will minimize drudgery and increase productivity in low input agriculture. Cultural weed control has been reviewed repeatedly, including a recent review by Shenk (1994) but the plight of smallholder farmers in developing countries has not changed significantly. This has happened because weed scientists have approached weed problems of developing countries using imported weed control technologies that are not fully applicable to the low input production systems that dominate agriculture in the tropics. Table 2 shows the subject matter distribution of papers published in the Nigerian Journal of Weed Science over an eight-year period. The subject matter distribution of the papers shows that a majority of them (45%) are on chemical weed control, biology and ecology of weeds account for 30%, while cultural control accounted for only 6% of the papers. There was surprisingly

Table 2. Subject matter distribution of papers published in NJWS (1988-95)[1].

Vol. ser. no.	No. of papers per vol.	Subject matter distribution of papers								
		Biol.	Ecol.	Cult.	Chem.	IWM	TEV.	ENQ	Econ.	Reviews
1	12	1	4	1	4	0	2	0	0	0
2	9	0	3	1	3	0	0	0	0	1
3	9	3	1	0	4	0	1	0	0	0
4	8	1	3	0	2	0	2	0	0	2
5	8	1	1	1	5	0	0	0	0	0
6	6	0	1	0	4	0	1	0	0	0
7	5	0	0	0	3	0	0	0	0	2
8	5	0	0	1	4	0	0	0	0	0
Total	64	6	13	4	29	0	6	0	0	5

[1]TEV. = Technology evaluation; IWM = Integrated weed management; ENQ = Environmental quality. Source: Akobundu, 1966b

no published research paper on integrated weed management, economic assessment of available weed control technologies under farmers' production conditions, and environmental quality studies (Akobundu, 1996b). This reflects a flaw either in subject matter training of weed scientists or funding for research. Several countries in the developing world do not have trained weed scientists and consequently little research is currently carried and hardly any publications are available on weed management.

Farmers in the developing countries of the world have very few improved weed management technologies to choose from. Development of improved weed management technologies has to be done within the context of the production circumstances in which farmers carry out their farming activities. There is often a lack of a reference point to assess the weed problems of farmers in low input agricultural systems. Many weed scientists fail to appreciate the problems of low input agriculture. Consequently, farmers' perceptions of what technologies will be appropriate to their farming circumstances are often overlooked or taken for granted by weed science researchers, especially if field tests show that the tested technologies make economic sense. Therefore it is important that potential improved weed management technologies for developing countries take farmers' perceptions about new technologies into consideration before these technologies are given to them. In order to develop improved weed management technologies for the low input farming systems of developing countries, there is need to fully understand the agroecological conditions and circumstances responsible for the transformation of tropical vegetation from a resource to an agricultural pest (weeds).

<u>Transfer of weed management technology: opportunities and problems</u>.

Progress will be made in the development of weed management technologies for smallholder farmers if research addresses the difficult problem of finding alternatives to hand weeding. Akobundu (1992) reviewed some of these alternatives. Before then, Hatem (1970) had stated that weed scientists aiming at solving weed problems in the tropics "must generate creative ideas and use them practically and economically to overcome problems such as lack of extension services, restricted credits, and unavailability of inputs." Weed problems of low input agriculture are compounded by the low resource base of farmers and the fact that there are so few weed control technologies whose economics of use are based on the farm sizes of these farmers. Hand weeding either by pulling weeds off or by hoe weeding still dominates the agriculture of low input farmers in these countries. There are very few improved weed control technologies that have reached the on-farm level of testing to date mainly because there is either nobody to carry out the field tests or no logistic support for them. In spite of what has been said or written to date, hardly any improved method of weed control has been packaged and field-tested to meet the special needs of low input farmers. Since very few developing countries have up to one trained weed scientist, it should be no surprise if the national extension services do not have weed management components. Generally, extension personnel have poor motivation and do not have transportation facilities. Improvement in extension delivery system should include training that has a weed management component as well as necessary logistic support for extension personnel.

<u>Presence of professionally trained weed science personnel</u>.

There is a widespread shortage of professionally trained weed scientists in developing countries of the world. In the few countries where trained personnel exist, only a negligible few have the right quality training that will inspire them to carry out research confidently on their weed problems. Generally the number of trained persons is so low that hardly any visible sign of good weed research is evident even to a casual observer. It is recognized that proper weed identification is necessary for weed management research and documentation but this in turn requires some expertise in plant taxonomy to train the trainers. Proper understanding of weed biology and weed/crop interactions requires that researchers be properly trained. Products of short courses cannot, without guidance, undertake finding solutions to fundamental problems associated with weediness, weed ecology or weed population dynamics. The complex interactions involving weeds, soil, physical environment and human actions often result in such dramatic shifts in weed flora that control measures require an in-depth understanding of those factors responsible for changes in weed flora and the associated weed problems. This then calls for proper training in weed science to give the researcher the confidence to undertake the strategic as well as the applied research.

Training of weed scientists in developed or developing countries has not always taken into consideration the enormous challenges that the trainees would face in the tropical environment where literature is in short supply, there are few experienced weed scientists on the field, and funding for research is low. The lack of focused training in weed science for people from developing countries is a primary limitation to the development of weed control as a science in this part of the world. Without the critical mass of well-trained weed scientists on location in developing countries, progress will be a little too small each time.

Effective technology transfer mechanism.

Effective technology transfer mechanism is an essential component of basic elements of improved weed management. These improved weed management technologies will only be useful if they can be transferred to farmers who can use them. Many developing countries have poorly developed extension services. Consequently, farmers are generally unable to benefit from research innovations. The emphasis on technology development should include a delivery system that will ensure that technologies that have been field-tested and found to be economical can be successfully transferred to the end user farmers.

CONCLUSIONS

Weed scientists should be committed to minimizing drudgery in agriculture, especially those of the developing countries of the world through the development of improved weed management technologies that will be appropriate for these environments and which will support food production on a sustainable crop yield basis. Weed scientists interested in the development of improved weed management technologies for developing countries should address the basic causes of weed infestation in smallholder farmers' fields. They should develop alternatives to hand weeding, and these alternatives should be those that minimize the drudgery associated with traditional weeding practices. These improved weeding practices should make farming more attractive and profitable, prevent soil degradation, environmental pollution, and a build-up of weed population pressure on arable lands. FAO should take advantage of existing inter-governmental communication channels to encourage the development of: (1) technologies that make farming attractive, reduce drudgery, reduce soil degradation, and sustain yields in developing countries, and (2) functional weed management technology transfer mechanisms as an integral part of each developing country's agricultural extension programme.

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BASIC ECONOMIC CRITERIA FOR IMPROVED WEED MANAGEMENT IN DEVELOPING COUNTRIES

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SUMMARY

The economic impact of weeds extends from fields to farms to regions and countries. Any analysis of weed problems can look at one of these levels or several. At the national level significant benefits will accrue with quarantine systems for the country and within the country via seed certification systems.

In analysing farm and field level annual cropping systems in developing countries, it is clear that herbicide use will tend to increase. In multi-cropped rice systems this will bring a real danger of herbicide resistance developing. Improved weed management may mean changes in land use, where this involves a perennial crop like rubber, subtle factors such as choice of most appropriate cultivar may have a greater economic impact then other forms of weed control.

I. INTRODUCTION

The literature on the economics of weeds is often only concerned with the single field, single crop level in mind but the impacts of weeds and their control extend to regional and national levels. In this paper we shall consider some of the broader, national issues involved with weeds and examine two contrasting farm level examples of weeds in developing countries. From this, we derive some guidelines for weed control policy, extension and research for the future.

II. THE IMPACT OF WEEDS

The impact of weeds and their control flows from field to farm to region and country and beyond.

In developing countries weeds have been traditionally controlled by hand with the work usually being done by women and sometimes children. Although most farmers are often aware of the impact of weeds on their crops, the community at large is frequently ignorant of the magnitude of the effects of weeds. One reason for this is the fact that weeds are usually insidious in their competitive effects unlike the more obvious insect and disease damage. Relatively low densities of weeds can cause significant economic loss.

The gains from weed control are also often not fully appreciated by the wider community. Yet efficient weed control can have the effect of reducing commodity prices for consumers (see Auld, Menz and Tisdell, 1987).

2.1 National level

The subtlety of the effect of weeds and their consequent underestimation as problems has often led to relatively low investment by governments and agricultural agencies in weed control. In several developing countries weed control, research and extension is often poorly supported. Hence there is value in demonstrating the magnitude of the economic effect of weed problems to authorities. Given that some resources are allocated at national level there are some practical ways in which governments should respond to weed problems.

While many developing country weed problems are due to native species, increased trade and communications will undoubtedly mean that more exotic species will become weeds. Effective quarantine systems at airports and sea ports will become more important to prevent new weed problems.

Within developing countries laws designed to stop the spread of weeds, such as noxious plant laws, require a strong and widespread regulatory presence and may not be practical. However, other strategies are available.

In most developing countries farmers tend to use their own crop seed, or similar seed from a neighbour, which is often contaminated with weeds (Table 1).

Table 1. **Rice Seed Contamination**

Number of Weeds Seeds/kg rice 1995-6		
Vietnam	Malaysia	Thailand
60.4	***19.0***	***31.0***

After Vo Mai, 1997

The establishment and fostering of seed certification schemes is a useful way to curtail the spread of weeds and reduce the impact of weeds in the sown crop.

With exotic weeds, the possibility of classical biocontrol should be considered, especially when agents have already been proven in another country. However, as many weeds in developing countries are natives, the possibility of producing bioherbicides should be considered by government agencies.

2.2 Farm and field level

To estimate the losses from weeds, experimental procedures are often used comparing a weed-free treatments (a) with a completely uncontrolled treatment (b) and perhaps, a new or experimental treatment.

While this has merit as scientific method, neither of the former (a) and (b) treatments relate to a practical situation. There is rarely a situation where weed control is 100% effective and in the course of normal cultural activities some level of weed suppression occurs.

Thus comparisons for assessing the impact of weeds should be made between (c) normal crop production activities (excluding activities directed at specific weed control) with (d) a deliberate, practical and effective weed control procedure. Economic assessments of new control methods should be within the comparison context of the (c) and (d) practices.

On a farm, decisions about controlling weeds are not made in isolation from other activities which compete for time, labour and cash. However, for the purposes of the following discussion, the field in which the weeds occur is considered in isolation.

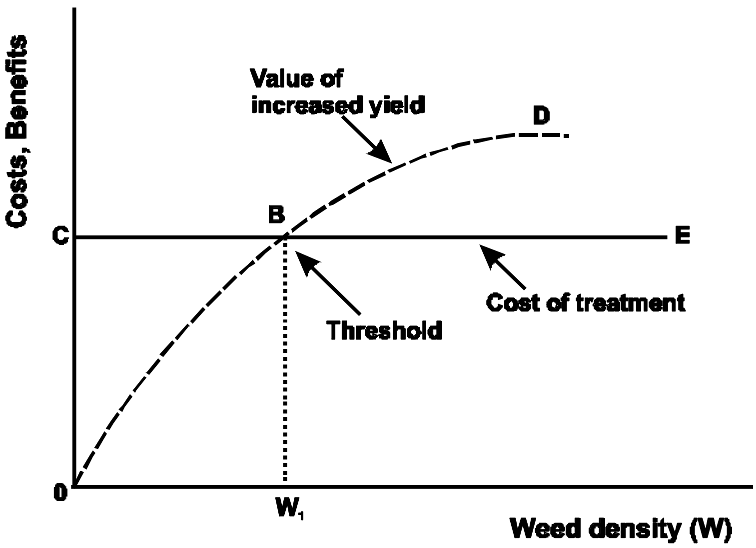
The effect of single species of crop weeds on yield is well documented. Crop yield decreases but at a decreasing rate with increasing weed density. Thus marginal benefits from controlling weeds decrease with increasing weed density.

The situation becomes less clear if one is not dealing with an annual crop or an annual weed.

In the following we shall consider (i) an annual crop/weed scenario and (ii) a perennial weed problem.

III. WEEDS IN RICE

Annual weeds in rice generally conform to an analysis which can be applied to wheat, corn and other annual crops (Fig. 1).



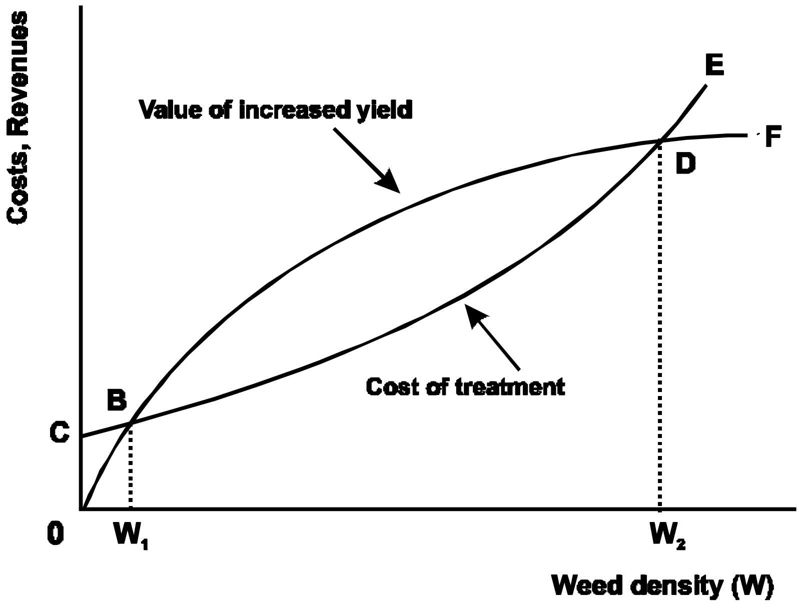
- Fig. 1 The economic threshold for treatment of a weed assuming that the treatment is fully effective. In the case shown, it is economic to treat the weed if its density exceeds W_1; treatment is not economic at lower weed densities. The cost of weed control (*CBE*) is assumed to be unrelated to weed density. *OBD* is the increase in revenue caused by weed control for the range of weed densities (from Auld *et al.* 1987).

- Weed control if done, for instance, by an overall herbicide spraying is independent of weed density (Fig. 1). The interaction of these factors has produced the concept of a point or threshold, where the mathematical functions, representing these relationships, intersect. In any cropping season, there will be an economically optimal level of weed control. However, if a longer term economic view is taken, considering reinfestation of seeds from uncontrolled weeds, the threshold weed density for control will be less than if only the perspective of a single year is taken.

- In reality, there is no precise point, step or threshold which can be pinpointed in advance because amongst other things, the value of increased crop yield from a given level of control is very season and price dependent and cannot be accurately predicted.

- Where weed control cost is not independent of density but, as in hand weeding, is more expensive as density increases, the cost line takes on a new direction.

- If labour is in short supply and weed control is competing with other activities on farm, then the cost of labour might increase at an increasing rate with weed density (Fig. 2).



- Fig. 2 Control costs (*CBDE*) increase at an increasing rate (because, say, of other demands on labour). There are two thresholds W_1 and W_2; control is only economic between W_1 and W_2.

- In Vietnam, the cost of labour is increasing in line with econimic growth and the cost of manual weed control is already about twice the cost of chemical control in rice (Table 2) and the cost benefit ratios of weed control by herbicide (cf. manual weed control) are higher (Table 3).

Table 2. **Cost of Weed control in rice** (US$/ha)
Red River Delta - Vietnam

	Manual	Chemical
Labour	100-120	20-25
Herbicide	-	15-20
Equipment	5-10	10-15
Total	105-130	45-60

After, Tan, Son, Trung (1997)

Table 3. **Benefit/Cost Ratios for Weed Control in Rice**

	Mekong Delta - Vietnam
Chemical Control	6.6 to 13
Manual Control	2.8 to 4.4

After, Chin (1997)

This has resulted in increased herbicide usage. Moreover, where the price of herbicide is low compared with the price of received for the crop, there is a tendency for prophylactic use of herbicides.

There are many uncertainties in relation to crop production, potential weed infestation and weed control which will influence the practical decision to control weeds. In addition, there is often uncertainty about the price of agricultural products which obviously has a significant bearing on economic thresholds.

It may be useful to consider a range of possible outcomes from weed control and work within this framework, considering a farmer’s attitude to risk (Fig. 3). A risk averse farmer will tend to control weeds at lower densities. In subsistence agriculture, risk aversion may be a relatively more important goal than profit maximisation. Various responses to risk in weed control are discussed by Auld and Tisdell (1987).

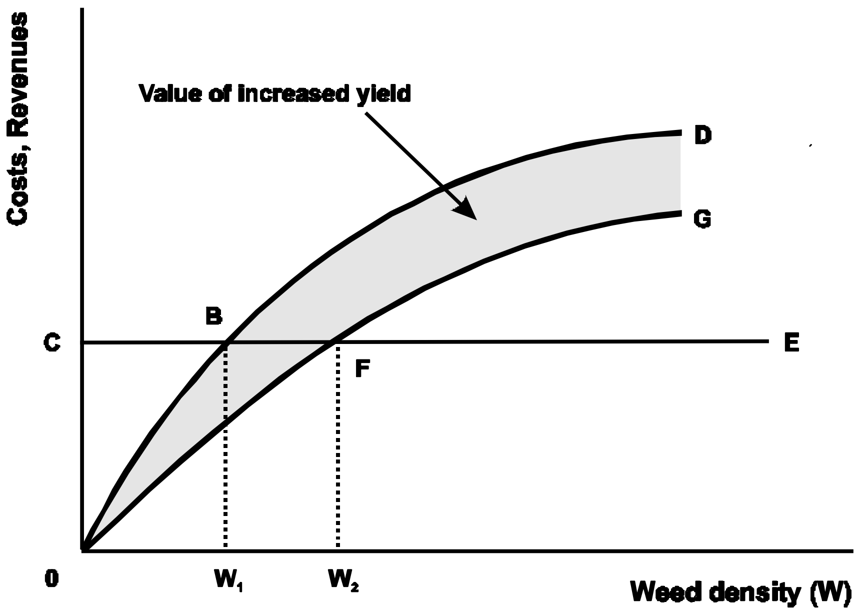


Fig. 3 Uncertainty about potential crop yield, its value and the benefits of weed controlled are illustrated by **a range of potential values of increased yield** and consequent range of critical weed densities between W_1 and W_2 (from Auld *et al.* 1987).

Where risk aversion is present, increased uncertainty about weed densities or the crop loss function tends to increase the probability that weeds will be treated at lower densities. In these cases specific experimentally determined economic threshold weed densities become less relevant to farmers' decisions to control weeds. Risk aversion may lead to the overuse of herbicides and consequently problems of herbicide resistance.

IMPERATA IN SOUTH EAST ASIA

Imperata grassland is widespread throughout deforested areas in the tropics. Their productivity is low as grazing land and their utility in shifting cultivation is declining but their area is vast. Their suppression by shading has suggested a role for trees and alternative land uses. Rubber is a suitable crop for some *Imperata* areas. Grist and Menz (1995) compared a number of strategies for establishing rubber plantations in *Imperata* areas in Indonesia. These included the use of upland rice as an intercrop, chemical weed control and their combination as well as the comparison of selected clonal seedlings with unselected seedlings (Table 4).

Obviously any economic analysis of a perennial crop and perennial weed requires a long term view. Some kind of modelling approach becomes a virtual pre-requisite and discounting procedures must be used to compare the economic net present value of options. In the present case, annual cash flows were discounted back to net present value using a 10% discount rate. Although many smallholders face significantly higher discount rates, large government-sponsored schemes often lend money at or below 10%. Ten percent was regarded as sufficiently large to penalise treatments with long payback periods.

Table 4. **Net Present Value** (Rp 000)

	Planting Material	
Treatment	Unselected	Clone
Base Case	341	1,246
Intercrop 2 years	361	2,491
Chemical Control 2 years	790	2,969
Intercrop 2 years, Chemical Control 3 years	1,100	3,360
Chemical Control 5 years	1,760	3,730
Average	870	2,759

After, Grist and Menz 1995

Results indicated that the use of improved rubber planting material to enhance the shading of *Imperata* had the greatest positive impact on profitability (Table 4). When rubber tree growth and thus shading was enhanced by supplemental control of *Imperata*, via intercropping or chemicals, economic returns are boosted further.

The potential for alternative land use should always be considered in the face of a persistent, specific weed problem. In this case, the importance of crop planting material has been highlighted.

CONCLUSIONS

Increase in herbicide use in developing countries is inevitable as labour costs rise and overuse is likely in some situations. This will lead to increased environmental contamination and herbicide resistant weeds. Difficult to control weeds such as weedy rice will increase.

Increasing trade and movement of people will increase the rate of invasion of new weeds to many countries.

The use of contaminated crop seed and poor quality seeds perpetuates many weed problems.

Alternative land uses and crop rotations may be more appropriate than attempting to control weeds in the current crop.

RECOMMENDATIONS

There is a need for governments to extend information on correct use of herbicides to IPM trainers, extension specialists and to farmers. In addition extending information on integrated weed management is essential.

Effective quarantine policies should be adopted at airports and seaports.

Seed certification systems should be adopted, encouraged and publicised.

Research on classical biocontrol of exotic weeds and inundative biocontrol of native weeds should be encouraged.

Research on cultivar selection, planting density and other aspects of IWM, such as biological control, should be sponsored.

Research and promotion of alternative land use for intractable weeds should be undertaken.

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CONCLUSIONS AND RECOMMENDATIONS
(*Ways to Improve Weed Management Components*)

- One of the major constraints to increased crop production in agriculture of the developing world is persistent weed interference with crop growth which causes heavy crop losses and reduces the quality of produce. Weeds compete strongly with crops for light, water and nutrients, and may also exude or leach substances from roots and leaves, respectively, which are toxic to crops.

- High weed pressure is currently associated with increased land use intensity. Small farmers in such systems, particularly those in areas with high human population densities, lack the capacity to deal effectively with the high level of weed seed rain that may occur during crop growth, after crop harvest, and even during fallow periods, where soil degradation may ensue.

- More than half of smallholders' labour is devoted to weeding, which is normally carried out by women (often pregnant) and children. For this reason, weeds are considered a serious economic and social problem.

- Pressure to increase crop production due to high demand for food and reduced availability of cropland compels farmers to adopt more effective weed control practices, which should at the same time be ecologically friendly and economically feasible.

- New weed control methods should be attractive to small farmers. On the one hand, they should serve to reduce weed stand and increase crop yields; on the other, they should not interfere with the ecological balance nor should they induce problems to human health. Effective weed management should be an integral part of any crop management system.

- Improvement of weed control practices can be achieved by a thorough understanding of bio-ecological conditions leading to the abundance and long-term persistence of species in weed communities, as well as the agronomic factors involved (especially tillage and harvesting practices) and socio-economic factors influencing acceptance by farmers.

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- In addition, to underpin the improvement of weed management some basic data are required to facilitate understanding of the factors involved. These are as follows:

    (i) Long-term records of weed problems in crop areas to enable growers to anticipate the severity of weed infestations and crop yield losses, and recognize early changes in species-composition of weed populations. If yield loss predictions are not possible, keeping records of weed severity and species present in individual fields will help farmers make more informed weed management decisions.

    (ii) Accurate prediction of weed seedling emergence for better timing of post-emergence treatments and, more generally, weed management decisions. The periodicity of weed seed germination and the effect of land use systems on weed seed production need to be better understood in tropical and sub-tropical areas.

    (iii) The population dynamics of troublesome weed species need~~s~~ to be fully appraised; such data will serve to indicate the change in weed abundance that may result from changes in weed and crop management.

(iv) Improved knowledge of weed-crop interactions to allow determination of Critical Periods for competition would help farmers identify optimal times for weeding and thus improve net returns.One way to compare various weed densities and times of emergence and removal is to use simple empirical model such as **Time Density Equivalent (TDE).**

TDE is the density of weed plants emerging with the crop and competing until harvest that is equivalent,in terms of effect on the crop, to a given density of a cohort of weeds emerging at a given time and removed at another given time.

(v) In advanced rural areas of developing countries, assessment of economic thresholds offers the opportunity for evaluating the need for weed control action, and is an effective tool to reduce costs of weed control.

(vi) Also in these areas for the near future, use of data from weed demographic studies coupled with population models may allow reasonable predictions to be made on the growth of weed populations under different control strategies. Such an approach should be a basic component of future weed management systems. In this context it is advisable to use simple models based on relatively few parameters and concentrated on the most important weed species (*e.g. Striga* spp., *Echinochloa* spp., *Cyperus rotundus* L., *Orobanche* spp. and others).

- In parallel with the above knowledge, it is crucial to develop improved weed control technologies, particularly for low input agriculture. Such technologies may include various control measures, such as:

  (i) Use of crops with allelopathic effects, as has been reported for rice.
  (ii) Crop rotation, planting density and intercropping.
  (iii) Identification of traits contributing to the competitive ability of cultivars for further selection of genotypes tolerant to weeds.
  (iv) Development of augmentative biological control, including the possibility of application of mycoherbicides produced locally and supplied to farmers at a low price.

- Integrated weed management, as part of Crop Management Systems, does not deny the rational use of any control method, including chemical weed control.

- An increase in herbicide use in developing countries is inevitable as labour costs rise. Many farmers are switching to use herbicides which are decidedly beneficial for crop production, but difficulties arise when these chemicals are used by untrained and inexperienced applicators. This will lead to increased environmental contamination and herbicide resistant weeds, e.g. weedy rice.

- In order to avoid the above problems, governments should disseminate information on the correct use of herbicides to IPM trainers, agricultural extension specialists and farmers. Regular training on these issues is essential for sound weed management development.

- The introduction of Herbicide Resistant Crops (HRC) into the farming system may facilitate the use of less toxic herbicides, and improve the cost-effectiveness and profitability of weed control. However, too hastily adoption of HRC may result in irreversible damage to the agro-ecosystem, by increasing the dependence on chemical control methods and tempting the farmer to use higher rates and repeated applications of herbicides. Above all, the selection pressure on the weed population may increase and that will shift it toward higher infestation with troublesome weeds and faster evolution of herbicide-resistant weeds.

Hence it is essential to conduct analysis of risk assessment before introducing any HRC into the agricultural practice.

- Weed management also includes some control activities out of the context of the crop cycle, e.g. increased trade and communications will undoubtedly mean that more exotic species become weeds. In order to avoid the introduction of such weed species into the territories of developing countries, effective systems should be implemented, such as:

  (i) Quarantine procedures at airports and seaports.
  (ii) Seed certification systems

- The main responsibility in the development of improved weed management lies with agricultural research and extension work. This involves switching research focus from the comparative study of individual intervention events (*e.g.* trials of new herbicides) to ecological and systems analysis at weed species, weed community and agro-ecosystem levels. Any efforts in this direction should seek to find alternatives to reduce hand weeding at small farming system.

- As appropriate, weed research should be conducted in both farmers' field areas as well as in research stations. Farmers can be come effective partners in these efforts, so it is advisable to train them in methods for scouting fields and identifying weed species. Farmers may also learn to collect soil samples from various fields, place the soil in containers, and identify and count weed seedlings.

- Critical responses to, and non-acceptance of, 'top-down' advice on pest management from extension workers by farmers is well known, and this strongly suggests that transferring the results of ecological research embodied within integrated weed management practices to farmers will involve more than just demonstration plots. There is a need to illustrate, to both extension workers and farmers, the *application* of ecological knowledge. Farmer field schools (FFS), along the same lines as those developed by FAO for insect control in the Intercountry programme on IPM in rice in South & Southeast Asia, illustrate the importance and success of the farmer participatory-orientated approach in this regard.

- The above success of FFS in IPM projects can also be used effectively to develop improved weed management at the field level. Through this method, principles of sound weed management could easily become an important part of the curriculum of simple protocols to assist farmers to conduct their own crop yield loss studies. In this context, farmers may conduct various activities to obtain basic information on weeds, including:

  (i) potted soil samples for analyses of seed banks and potential infestations
  (ii) comparison of crop varieties for weed-suppressive attributes, either through crop architecture or allelopathy.
  (iii) simple tables or charts of emergence of different weed species

(iv) comparison of mulches or cover crops
(v) simple plots for studies of weed-crop competition

- These studies at FFS also guarantee a vital connection between weed science and farming practice and strengthen the interest of farmers and advisers in facts and problems. Results from a number of studies conducted by farmers within a geographical region could be combined to produce crop yield loss prediction tables.

- FAO, in close cooperation with other agencies and the donor community, should take advantage of existing inter-governmental communication channels to encourage the development of weed management as an important aid to reduce drudgery, reduce soil degradation and sustain crop yields in developing countries. Such development is highly feasible if the appropriate weed management component is included in all IPM projects.

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