**CROP PROTECTION PROGRAMME**

# Minimising the economic and sociological impacts of *Phalaris minor* in rice-wheat ecosystems

**R7331 [ZA0284]**

# FINAL TECHNICAL REPORT

**1 January 1999 – 30 June 2002**

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Date FTR completed: 28 June 2002

**This publication is an output from a research funded by the United Kingdom Department for International Development for the benefit of developing countries. The views expressed are not necessarily those of DFID.** R7331 Minimising the economic and sociological impacts of *Phalaris minor* in rice-wheat ecosystems

# Executive Summary

This project addressed the wider economic and sociological impacts of the *Phalaris minor* epidemic in Haryana, northern India, using four complementary research approaches. [1] a socio-economic audit to assess the contribution which environmental, management and socio-economic factors have upon the population dynamics of *P. minor*, [2] biological and ecological-based research using field experimentation to design a simulation model of the population dynamics of *P. minor*, [3] a programme of education and training based upon the audit and modelling studies for Indian scientists and extension officers and [4] an assessment of the genetic variability of *P. minor* biotypes in relation to ecological/agronomic impact.

The socio-economic audit [1] gave evidence for the existence of classes of farmers in Haryana with different socio-economic backgrounds, who had unequal access to information on farming and varied in their ability to adopt technical innovations aiming to improve *P. minor* control. This worrying trend may lead to widening differences in the adoption of technology and socio-economic strength between farmer classes in the future and ultimately result in expulsion of many small farmers out of farming. Social consequences of disappearing rural livelihoods may be grave. Studies on the biology and ecology of *P. minor* [2] showed that *P. minor* is a highly reproductive grass that easily adapts to changing environmental conditions and weed control methods. Indications of cross resistance against newly introduced herbicides have been found, while application of new cultivation techniques such as zero-tillage can provide significant, albeit short-term reductions in competition from *P. minor*. Rotating wheat with other winter crops is a method that can provide long-lasting control of *P. minor*, but due to the government's policy of supporting cultivation of food grains, farmers are unwilling to incorporate other crops in their rotation.

Education and training [3] resulted in the adoption by HAU staff of new statistical and modelling approaches in their agronomy and weed science research programmes. Furthermore, outputs from the modelling workshop enabled HAU staff to design a new course for MSc and PhD students of agronomy. The molecular ecology research [4] has confirmed *P. minor* as an inbreeding weed which is differentiated genetically within and between populations, on a geographic basis. Practical crop management measures require to be undertaken to prevent undue selection pressure on *P. minor*, with the resultant development of 'weedy' biotypes including further herbicide resistance.

This project contributes to our understanding of why *P. minor* can be a serious economic cost to farmers. It identifies good farming practice and the social groups which are most disadvantaged in their knowledge/ability to control the weed. Improvements in our socio-economic understanding of *P. minor* are underpinned by new biological and quantitative research. For example, the impact of crop rotations and management practices can be assessed in relation to a new model describing the growth and life cycle of *P. minor*. Furthermore, end users of the research can benefit from the local programme of training implemented within the Indian University system.

# Background

## Historical Perspective

The fertile Indo-Gangetic plains in northern India is a region that is highly suitable for intensive cropping systems providing food grains for millions of people. The intensive rice-wheat cropping pattern allowed *Phalaris minor* to become a ubiquitous weed infesting more than 16m ha of wheat, causing wheat yield losses up to 80%. The weed has hitherto been controlled by the phenyl-urea herbicide isoproturon, but the development of isoproturon resistant biotypes of *P. minor* in the early 1990s drastically reduced the control. Due to farmers' failure to recognise early symptoms of resistance in the field, isoproturon-resistant biotypes have now infested large areas of Haryana, Punjab and Uttar Pradesh. Introduction of the herbicides fenoxaprop-P-ethyl, sulfosulfuron and clodinafop-propargyl, with alternative modes of action controlling resistant biotypes, has drastically improved *P. minor* control from the late 1990s. However, first signs of cross-resistance of *P. minor* biotypes against the newly introduced herbicides have appeared [2001], especially fenoxaprop, and it is doubtful whether the present herbicides can provide a long-term solution to the *P. minor* epidemic. Newly introduced soil cultivation techniques, such as zero-tillage and raised-bed planting, offer alternatives to improve weed control. As *P. minor* poses a serious threat to the sustainability of wheat production on the Indo-Gangetic plains, there is a strong need to find alternative ways to control the weed. In addition, the wider socio-economic impacts of the *P. minor* epidemic need to be assessed to increase the chances of wide-spread adoption of new production technologies aiming to improve the sustainability of wheat production.

## What Did We Know About *Phalaris minor*?

A good insight of the nature of isoproturon resistance and the changes in physiology responsible for the resistance characteristic was obtained by Singh [1998], who conducted a PhD programme in the UK devoted to the physiological and biochemical basis of the isoproturon-resistance in *P. minor*. Knowledge of the biology and ecology of *P. minor* in the rice-wheat system was rather limited. The effect of herbicide applications on *P. minor* population size later in the season was tested in various trials. However, knowledge of seedbank dynamics, seedling emergence and seed production was almost entirely missing, limiting the possibilities to predict the long-term effect of weed control measures on the *P. minor* population size. Also, little knowledge was available of the genetic variability of different *P. minor* biotypes and the rate of gene flow between populations, which is important for predicting the demography of resistant populations and the chances that *P. minor* may develop cross-resistance against one of the newly introduced herbicides. In addition, little was known about the wider agronomic and socio-economic context of the *P. minor* epidemic, especially how farmers with different socio-economic backgrounds vary in their perception of the weed epidemic and their ability to adopt newly introduced cultivation techniques aiming to improve weed control.

In Haryana, Professor Malik and his team working at the Agronomy Department of CCS Haryana Agricultural University [HAU] have gained extensive experience in conducting research in the control of *P. minor* using chemical and cultural techniques. However the scientific staff lacked expertise on data handling, statistics and modelling techniques. Collaboration between SAC and HAU offered the opportunity for SAC scientists to use the available practical experience at HAU with research in the biology and ecology of *P. minor*, while HAU staff could benefit from SAC expertise on data handling, statistics and modelling. In addition, collaboration with HAU provided the opportunity to work with other ongoing programmes at HAU funded by the World Bank and ACIAR [Australian Centre for International Agricultural Research].

# Project Purpose

Four areas of research endeavour can be distinguished:

## Ecosystem Audits

- To describe the influence of environmental, vegetation and management factors upon weed population biology and control, using a range of statistical techniques including multivariate analyses.

- To assess the contribution that farm socio-economic factors have upon the development of weed populations and farmers' ability to adopt innovative production techniques reducing *P. minor* pressure.

## Weed Life Cycle Studies

- To describe the demography and germination periodicity of *P. minor* as influenced by temperature and moisture and farmer cropping practices, using field data as well as quantitative and analytical models

- To predict the economic impact of *P. minor* in wheat/rice ecosystems, using the outputs of models.

## Education and Technology Transfer

To implement a programme of education and technology transfer for researchers and advisors with respect to:

[a] undertaking the ecosystem audit;
[b] utilising plant population models;

[c] identifying the key factors which can be used to minimise the economic and sociological impact of *P. minor*.

## Weed Genetics

To assess the genetic variability within and between *P. minor* biotypes and its ecological/agronomic impact.

# Research Activities

The project's research activities as presented in the original project proposal fall into three categories: ecosystem audit, weed life-cycle studies, and education and technology transfer. A fourth [supplementary] research activity, assessment of the genetic variability of *P. minor*, was added later [2000] to the research proposal.

## 1. Ecosystem Audit

Socio-economic surveys were undertaken over 2 years in Haryana to characterise the agronomic and socio-economic background of the *P. minor* epidemic and to identify the key factors that contribute to the weed epidemic.

### 1.1 Establishment of survey regions and farmers to participate

A system audit was conducted consisting of two surveys of respectively 118 and 102 Haryana farmers interviewed at the end of the wheat growing season in March 2000 and March 2001. Farmers were identified following a stratified random sampling method. The strata were three geographically and edaphically distinct regions in Haryana. Farmers working in the fields were randomly approached and interviewed.

### 1.2 Collect and analyse socio-economic data

The survey included items on general land management practices, weed control as well as socio-economic and psychological indicators. Multivariate analyses were used to interpret the survey data. Farmers were classified based on geographic, climatic and environmental conditions as well as socio-economic indicators. These farm classes in turn were related to field management, access to information on farming, *P. minor* pressure in the field and the occurrence of herbicide-resistance.

### 1.3 Data interpretation

Results of the survey are discussed below in the Outputs Section and in a refereed paper submitted to *Experimental Agriculture*.

## 2. Weed Life Cycle Studies

Assessment of *P. minor* soil seedbank dynamics, plant emergence, growth and seed production as affected by various weed control strategies and tillage regimes were assessed. These data permitted the development of a weed population model.

### 2.1 Soil seedbank studies

In the original proposal, research activity 2.1 only included weed dormancy assessments. This research activity was expanded to include new studies to determine the effect of straw burning on seed germinability and the effect of various ploughing systems on vertical seed distribution in the soil. Thus, a series of experiments have been conducted as follows:

[a] *P. minor* dormancy and seed longevity as affected by soil conditions and depth of burial;

[b] the effects of straw residue burning on survival and germinability of seeds buried in different soil layers;
[c] the vertical movement of seeds in rice-wheat and millet-wheat rotations as affected by cultivation techniques.

[a] *P. minor* seed longevity was assessed under a range of field and laboratory conditions. Specialised nylon net bags containing *P. minor* seeds were buried at various depths at HAU experimental farm, Hisar, or Uchani Regional Research Station, Karnal. Soil conditions at both location differed in texture, humidity and cropping system. Seed viability was assessed at monthly intervals by exhuming bags with seeds and testing the germinability of the seeds. Seed longevity experiments were initiated September 1999 and run until December 2001. A refrigerated seed incubator was purchased at HAU to provide optimum germination conditions for exhumed seeds.

[b] The effects of straw burning on the survival and germinability of *P. minor* seeds were tested in two almost identical field experiments. Viability of seeds buried in various soil layer was tested after burning various quantities of straw. The experiments were conducted in March 2001 and June 2001. In addition to the burning experiments, an oven study was carried out to test the germination behaviour of *P. minor* seeds after exposure to heat.

[c] The vertical movement of seeds in the soil as affected by cropping and cultivation pattern was tested using small glass beads mimicking the movement of *P. minor* seeds. Beads were spread on the surface in plots at the HAU experimental farm, Hisar, and Uchani Regional Research Station, Karnal before the summer crop in 2000. The effect of millet-wheat and rice-wheat rotations using different soil cultivation techniques on the relative vertical distribution of beads through the soil profile was assessed in December 2000.

### 2.2 Population flux studies

A two-year experiment was conducted in farmers' fields to assess the population flux of isoproturon-resistant *P. minor* biotypes in competition with wheat and how the population flux is affected by tillage regime and herbicide application.

The field experiment was conducted with the following objectives:

[a] to study how zero-tillage, compared with conventional tillage, affects vertical distribution of *P. minor* seeds through the soil profile, *P. minor* emergence rate for various flushes, *P. minor* growth habits throughout the season and final wheat grain yield;
[b] to investigate the effects of herbicide application on *P. minor* densities, individual plant weight of the various flushes and final wheat grain;
[c] to quantify the relationship between *P. minor* plant size and reproductive output and seed viability.

In season 2000-2001, the experiment was located at a farmer's field near the village of Pirthala, Fatehabad district, Haryana. The experiment was repeated in 2001-2002 at a farmer's field near the village of Narnodh, Hisar district, Haryana. The experiment was laid out using a split-plot design with fields under conventional and zero-tillage as main plots and weed control treatments as subplots. Weed control treatments included no weed control, application of isoproturon and application of three newly introduced herbicides: fenoxaprop-P-ethyl, clodinafop-propargyl and sulfosulfuron. The effect of conventional and zero-tillage systems on relative distribution of *P. minor* seeds through the soil profile and seedling emergence was assessed early in the growing season. HAU scientists were unfamiliar with soil seedbank assessment techniques and therefore, a technique for determining seed density in various soil layers was introduced and further refined at HAU. The technique made use of a soil seedbank sampler purchased in the UK and the limited laboratory facilities available at HAU. After herbicide application, the effect of weed control treatments on the mortality and biomass of various *P. minor* flushes and the biomass of wheat was assessed. At final harvest, the relation between plant size and reproductive output of various flushes of *P. minor* plants was established.

### 2.3 Run empirical models

Synthesis of the collected data on *P. minor* population dynamics was achieved using modelling techniques for simulations. Available knowledge on *P. minor* biology and its behaviour in competition with wheat was integrated in a new *P. minor* life cycle model, using Fortran Simulation Translator as a programming language. The model described the lifecycle of *P. minor* using five life stages: seeds in the soil, emerged seedlings, plant density at midseason [after herbicide application], adult plant density and seed production by mother plants [Figure 9]. The main processes externally regulating the population size were herbicide use, tillage regime and wheat competitive pressure. *P. minor* population size was intrinsically regulated by factors such as seed survival, germination and emergence rate, self-thinning and seed production. Three flushes of emergence were distinguished in the model: the first flush emerging along with the wheat, the second flush emerging after the first irrigation before herbicide application and the third flush emerging after the second irrigation after herbicide application.

## 3. Programme of Education and Technology Transfer for Researchers, Advisors and Master Trainers

### 3.1 Workshop conjoint with other institutions to review research/technology transfer existing status

This workshop was held 7-9 March 1999 in Haryana and brought together the DFID Australian and Indian research interests and funding programmes. The workshop identified:

[a] the key academic contacts in HAU and other Indian/International organisations;
[b] future events where inputs from the DFID project could be made;
[c] finalised the programme of workshops/education/training.

### 3.2 Select target groups of scientists/advisors for technology transfer from multivariate analyses and hold training workshop

This workshop on multivariate data analysis was held 13-15 December 1999, with 23 participants from Haryana, Punjab and Tamil Nadu.

### 3.3 Select target group of scientists for training in modelling and hold training workshop

This workshop on mathematical modelling in weed science, conducted 11-14 December 2000, was attended by 28 Indian researchers with various scientific backgrounds.

### 3.4 Select target group of scientists and advisors to review the utility of the scientific/socio-economic analyses and modelling predictions

Due to the war in Afghanistan, this review workshop was delayed, but finally successfully delivered on 18-20 March 2002, for 23 scientists from HAU and Uttar Pradesh.

Later, a fourth category was added to the original proposal in weed genetics:

## 4. Assessment of the Genetic Variability of *P. minor* via Molecular Techniques

### 4.1 Optimise PCR finger printing technique using a range of micro/mini satellite primers

The PCR fingerprinting technique was successfully optimised by SAC staff and HAU scientist Dr Saharan, who visited SAC in summer 2000.

**4.2 Collect seed of various *P. minor* biotypes in Haryana and conduct the genetic assessment**

Seed samples from 200 plants originating from four *P. minor* population in geographically distinct regions in Haryana were collected in April 2000. The genetic assessment was conducted by Dr Saharan at SAC in summer 2000 and later continued at HAU.

## 5. Additional Information

In addition to the above mentioned research activities, a study of literature has been conducted to the rice-wheat system in Haryana, the biology and ecology of *P. minor*, available weed control methods and the utility of modelling for developing weed control strategies. The study will be published as part of a PhD thesis in July 2002.

# <u>Outputs</u>

## 1. Ecosystem Audit

The audit showed that the *P. minor* epidemic is for many Haryana farmers a major production constraint, seriously affecting farm profitability. The survey suggested that the epidemic was closely entangled with geographic factors, as well as farm management and farmers' socio-economic position. Farmers were classified based on geographic location and on socio-economic situation. The geographic distinction was the result of regional differences in climatic and soil conditions and consequently, variation in cropping pattern, herbicide-resistant weed development and farm economics. Haryana farmers were divided into three groups, corresponding with different geographic areas. It was possible to distinguish the majority of the farmers from the three regions via a Principal Components Analysis using the variables farm size, *P. minor* density, herbicide expenditure and irrigation management [Figure 1].

Surveyed farmers were also stratified according to their profitability [Figure 2] and their socio-economic position [Table 1]. Profitable farms had lowest *P. minor* densities, highest herbicide expenditure and recognised *P. minor* as a more important threat for the farm profitability, compared with poorly profitable farms. The socio-economic stratification was based on variables such as scale of farming, number of cattle, mechanisation level, availability of hired labour and availability of additional income besides farming. Farmers with a strong socio-economic position favoured technical solutions to control *P. minor*, such as herbicides, while poor farmers preferred low-input control tools, such as crop varieties with high weed suppressing abilities. Socio-economically successful farmers had the most profitable farms and were most frequently visited by university and agricultural company representatives. In contrast, the use of broadcast media as a source of information on farming was widespread among the entire farming population.

**TABLE 1 Relationship between socio-economics and rating of weed control practices, farm profitability and percentage of farmers receiving advice on farming via university, government or company extension officers and media**

| **Socio-economic class**[1] | **1** | **2** | **3** | **4** |
|---|---|---|---|---|
| **Rating of weed control practices**[2] | | | | |
| Herbicides | 0.59 [0.06] | 0.74 [0.05] | 0.74 [0.05] | 0.84 [0.07] |
| Cultivation techniques | 0.47 [0.04] | 0.58 [0.04] | 0.54 [0.05] | 0.64 [0.06] |
| Wheat cultivars | 0.30 [0.02] | 0.28 [0.02] | 0.26 [0.03] | 0.21 [0.01] |
| Profitability[3] | 0.59 [0.02] | 0.66 [0.02] | 0.64 [0.03] | 1.00 [0.04] |
| **Information sources** | | | | |
| University | 11 [6.0] | 8.8 [4.9] | 28 [9.2] | 53 [13] |
| Other government | 18 [7.4] | 24 [7.4] | 40 [10] | 80 [11] |
| Agro-chemical company | 46 [9.6] | 59 [8.6] | 64 [9.8] | 93 [6.7] |
| Radio/TV/Newspaper | 86 [6.7] | 85 [6.2] | 96 [4.0] | 93 [6.7] |

[1] from class 1 to 4 increasing socio-economic strength
[2] 0 = poor usefulness for weed control
1 = high usefulness for weed control
[3] 0 = poor farm profitability
1 = high farm profitability

Variation in the socio-economic position of farmers and access to information on farming affected their ability to adopt agricultural innovations aiming to improve the sustainability of the rice-wheat system in Haryana. The present surveys showed that the Haryana farmer community cannot be treated as a homogeneous group that only differs in the their degree of innovation. Whereas farmers with a strong socio-economic position successfully adopted alternative herbicides in the areas infested with resistant biotypes, many farmers with a weaker socio-economic position did not achieve satisfactory weed control. This failure to adopt alternative herbicides could not solely be attributed to ignorance or conservatism of these farmers. It was likely to be related to other factors, such as poor access to capital and information and differences in psychological characteristics.

Extension agents in Haryana preferred to work with farmers with a strong socio-economic position, which was one of the reasons why the recently introduced technical innovations aiming to improve *P. minor* control, alternative herbicides and zero-tillage, were most rapidly adopted and best appreciated by farmers with a strong socio-economic position. The survey suggested that farmers with a poor socio-economic position were likely to benefit more from low-input ways of controlling *P. minor*, such as diversification of the cropping system and wheat varieties with improved weed suppressing abilities. These means of controlling *P. minor* have received little attention so far from agricultural scientists and policy makers. Consequently, little progress has been made on this front over the last decade.

An obvious consequence of introducing innovations targeted at resource-rich farmers is that the technology and income gap between resource-rich and resource-poor farmers widens, which may ultimately result in the exclusion of rural people out of farming and further consolidation of the scale of farming in Haryana. While this consolidation may be beneficial to increase national grain production, improve the efficiency of production and make the Indian agriculture more competitive on the world market, the social consequences of disappearing rural livelihoods, without availability of alternative employment, may be grave.

# 2. Weed Lifecycle Studies

## 2.1 Soil seedbank studies

Studies to the seed longevity of *P. minor* revealed that seed half-life time was under many conditions limited to less than a year [Table 2], but seed longevity was prolonged when seeds were deeply buried under anaerobic circumstances [Study 2 at Karnal]. Seed longevity in the field was much shorter than the longevity of seeds stored under laboratory conditions. The observed short longevity in the field explains why alternative winter crops preventing *P. minor* seed set strongly reduce the weed population in the subsequent year.

**TABLE 2 Half-life time after burial and time until no germination occurred in seed longevity studies [months]**

| Study | Site | Depth [cm] | Half-life | No Germination |
|---|---|---|---|---|
| 1 | Hisar | 30 | 7.1 | 10 |
| 1 | Karnal | 30 | 16.7 | 21 |
| 2 | Karnal | 20 | 11.3 | 14 |
| 3 | Hisar | 0 | 5.8 | 7 |
| 3 | Hisar | 5 | 4.0 | 10 |
| 3 | Hisar | 10 | 3.3 | 11 |
| 3 | Hisar | 20 | 2.9 | 10 |
| 3 | Hisar | 30 | 3.1 | 11 |
| Literature | Lab | | 4 years | 8.5 years |

Studies on the effect of various tillage systems on the vertical movement of beads through the soil profile showed that zero-tillage sowing left most of the beads undisturbed on the soil surface, while conventional tillage using local machinery moved few seeds below 10cm depth [Figure 3]. Mouldboard ploughing resulted in a higher fraction of seeds below 10cm depth. This indicated that mouldboard ploughing may help to reduce weed population as *P. minor* seeds fail to germinate when buried below 10 cm depth.

Straw burning killed all *P. minor* seeds lying on or near the soil surface, while the germinability of seeds covered with soil was less affected [Figure 4]. In farmers' fields, this implies that wheat straw burning may kill many of the recently shed *P. minor* seeds. Rice straw burning is conducted when *P. minor* seeds are incorporated into the soil and may have little impact on the germinability. Rice straw burning has often been associated with increased seedling emergence [Singh *et al*., 1999], which is probably related to the improved environment for seed germination after burning rather than a direct stimulatory effect of burning on seed germinability. As rice straw burning is associated with negative side effects, such as air pollution, loss of soil organic matter and enhanced *P. minor* seedling emergence, incorporation of straw may be preferred to burning.

## 2.2 Population flux studies

The population flux studies revealed that zero-tillage, in comparison with conventional tillage, diminishes *P. minor* pressure by reducing the emergence rate of first flush seedlings, which are most important for crop-weed interaction later in the season [Figure 5]. The reduction in emergence rate of around 50% in plots under zero-tillage may be attributed to a lack of soil disturbance and enhanced crust formation on the surface, hindering *P. minor* seeds in the upper layers to germinate and hindering seedling from lower soil layers to emerge. Apart from a reduction in emergence rate, zero-tillage had little effect on the growth and development of *P. minor* plants. Coefficients of the regression analyses relating soil seedbank density with seedling density were comparable with those found in published studies, suggesting that the newly developed technique for soil seedbank sampling using simple laboratory facilities at HAU was of similar value to those used by other scientists.

Comparison of *P. minor* density and biomass in various herbicide treatments showed that the biotypes used in the experiments were completely resistant against the recommended dose of isoproturon [Figure 6 a-b]. In addition, there were strong indications that the *P. minor* biotypes were cross-resistant against the newly introduced herbicide fenoxaprop. Even though first signs of resistance of *P. minor* against fenoxaprop in Haryana have been published [Yadav *et al*., 2002], the high levels of cross-resistance as found in the present experiments have not been reported before. In addition, the density of *P. minor* plants in control and isoproturon-treated fields diminished during the growing season, indicating that, besides herbicide-dependent mortality, self-thinning and wheat competitive pressure are important factors regulating the population size.

Strong evidence was found for a linear relationship between reproductive output and plant vegetative weight [Figure 7a]. The trendline's intercept with the x-axis in Figure 7a did not significantly differ from zero, indicating there is no real threshold size for seed production.

Thousand seed weight of *P. minor* varied between 1.2 and 2.2g and was only slightly influenced by vegetative weight of the mother plant [Figure 7b]. *P. minor* plants with a small vegetative weight had a reduced number of seeds rather than reduced weight of the individual seeds, which suggests that seeds from plants varying in size were equally fit.

### 2.3 Modelling studies

The first simulation showed a sigmoid increase in *P. minor* densities [Figure 10a]. Even though weed control rates as achieved by clodinafop were used as input parameters, population densities stabilised around 2000 and 3000 plants $m^{-2}$, which is far beyond maximum *P. minor* densities found in the field. Closer examination of the simulation data revealed that, during the first year of simulation, seedling density, final plant density and subsequent seed production were in line with experimental data. However, the soil seedbank density drastically increased after the first seed shed and subsequently, during the second year, seedling and adult plant density also dramatically increased. The model did not recognise losses from the stage of seeds on the mother plant to the stage of seeds in the soil before emergence, as no such data were available. Comparison of the model with observed data made it plausible that large losses occur between seed production and soil seedbank density at the beginning of the following growing season and this endemic control may be very important in regulating the population size. Manipulation of this endemic control may offer new opportunities to improve weed control. To enable further simulations, the model was calibrated by including a mortality parameter for recently shed seeds, which was set at 0.8, assuming that 80% of the recently shed seeds fail to survive until the beginning of the subsequent growing season.

After calibration, the model was run for various weed control scenarios [Figure 10b]. Isoproturon application only slightly reduced *P. minor* densities compared with no herbicides. Application of zero-tillage techniques was more beneficial than application of isoproturon. Clodinafop provided good control of *P. minor*, irrespective of the tillage system. Even under the best weed control strategy, *i.e.* clodinafop application along with zero tillage, it would take 17 years until the weed density is below 1 plant per ha and can be considered eradicated. Weed eradication is therefore not a realistic weed control goal.

An alternative weed control strategy is alternation of wheat with other winter crops preventing *P. minor* seed shed [Figure 10c]. The model suggested that this weed control strategy is viable, but only in combination with zero tillage techniques. In addition, the model indicated that a two-year sugarcane crop, which is a common crop in the rice-wheat belt of Haryana, would allow productive cultivation of wheat without the use of herbicides for two subsequent years. Figures 10c showed that the relative advantages of zero-tillage in terms of *P. minor* reduction are greatest when herbicide inputs are low. Furthermore, the results indicated that wheat cultivation under herbicide-free conditions can be productive in Haryana, but half the land suitable for wheat cultivation should be set aside for alternative winter crops.

## 3. Programme of Education and Technology Transfer for Researchers, Advisors and Master Trainers

Four workshops have been conducted following the original project proposal. Workshop manuals have been prepared for workshops II, III and IV [Activity 3.2, 3.3 and 3.4 respectively]. The number of participants typically varied between 20 and 30 scientists. Most participants belonged to one of the Indian agricultural universities.

## 4. Assessment of the Genetic Variability of *P. minor* via Molecular Techniques

Essentially, the molecular data provided an insight towards understanding the reproductive biology of *P. minor* and the ecological significance of this behaviour. The genetic fingerprinting illustrated the extent of molecular similarity as influenced by [a] the individual plant and [b] the sample site location. Figure 8 and Table 3 illustrate comparisons using the molecular data.

It was evident that in this inbreeding species, plant to plant genetic variation was detectable but in addition, populations varied from site to site [Figure 8a]. Outcrossing between plants was relatively low, given the high degree of similarity within and between the plant populations sampled [Table 3]. Heterozygozity values assessed using a method from Zhivotovsky [1999] suggested that the four populations of *P. minor* ranged in value from 0.23-0.27.

In ecological terms, *P. minor* can be described as a self-pollinating inbreeder. Levels of polymorphism are therefore low [10-17%] with associated low levels of heterozygozity [0.23-0.27%]. In practical terms, the self-pollinating nature of the weed will increase its probability and rate of evolution of favourable recessive mutations e.g. herbicide resistance. This is a key determinant in contributing to the continuing economic losses caused by *P. minor*.

The molecular data can also be used to consider the factors which influence the differentiation of *Phalaris* populations i.e. why they become functionally distinct. Accordingly, *P. minor* will evolve or differentiate as influenced by the extent of self-pollination, founder effects, spontaneous mutations and selection [e.g. constant herbicide use]. In addition, while the geographical location of the population provides genetic distinctiveness, this may be affected by the way farmers crop the land, irrigate and harvest. Crop production practices should be encouraged which minimise the selection pressures on *Phalaris* and therefore help to prevent the evolution of more weedy biotypes.

**TABLE 3 Intra* and inter population similarities in *P. minor* as assessed via molecular markers**

| Population | Percentage Similarity | | | |
|---|---|---|---|---|
| Hisar | 86.5* | | | |
| Lalhoda | 78.4 | 88.4* | | |
| Karnal | 83.1 | 83.4 | 86.1* | |
| Jajhar | 82.1 | 84.4 | 85.4 | 90.2* |
| | Hisar | Lalhoda | Karnal | Jajhar |

# Dissemination Outputs

## Activity 1: Socio-economic Audit

| Reference Type | Citation Details | In prep/ submitted/ published |
|---|---|---|
| Peer-reviewed Paper | Franke, A. C., McRoberts, N., Marshall, G., Malik, R. K., Singh, S. and Nehra, A. S. [2002]. A survey of *Phalaris minor* in the Indian rice-what system. *Experimental Agriculture.* | Submitted [1] |
| Peer-reviewed Paper | Franke, A. C., McRoberts, N., Marshall, G., Malik, R. K., Singh, S. & Nehra, A. S. [2002]. Aggregation in innovation diffusion models for agricultural systems. *Agricultural Systems.* | Submitted [2] |
| Thesis | Franke, A. C. [2002]. Ecological and socio-economic aspects of the *Phalaris minor* epidemic in northern India. *PhD thesis, Scottish Agricultural College & Glasgow University.* | In prep. [3] |
| Poster | Franke, A. C., McRoberts, N and Marshall, G. [2002]. Relation between annual rainfall and demography of isoproturon-resistant *Phalaris minor* in Haryana. *To be presented at International Workshop: Herbicide resistance management & zero tillage in rice-wheat cropping system, Hisar, 4-6 March 2002*. | Published [4] |
| Poster | Franke, A. C., McRoberts, N. and Marshall, G. [2000]. A farmers' survey to assess *Phalaris minor* in the Indian rice-wheat system. *SAC Research Conference 7-8 September 2000, Aberdeen* | Published [5] |
| Newspaper Article | Franke, A. C. and Franke, B. [2002]. Canarygrass epidemic threatens wheat cultivation in northern India [In Dutch]. *Natuur & Techniek* **70** [1]: 54-59. | Published [6] |
| Newspaper Article | McRoberts, N. [2001]. Having a bubaly time. *SAC News*, **11** [3]: 6. | Published [7] |
| Newspaper Article | Franke, A. C. [2001]. Small weeds, big issues. *SAC News*, **11** [4]: 10. | Published [8] |
| Newsletter Article | Franke, A.C. [1999]. *Phalaris minor* major mission. *SAC News* **9** [5]: 7. | Published [9] |
| Newspaper Article | Marshall, G. [1999]. Rice, wheat and that weed. *SAC News* **9** [2]: 11. | Published [10] |
| Lecture | Marshall, G. [1999]. Key developments in the management of multi-disciplinary research. *Lecture at Haryana Agricultural University, Hisar, India, 13 December 1999.* | Published [11] |

## Activity 2: Weed Lifecycle Studies

| Reference Type | Citation Details | In prep/ submitted/ published |
|---|---|---|
| Peer-reviewed paper | Franke, A. C., McRoberts, N., Marshall, G., Malik, R. K., Singh, S. & Nehra, A. S. [2002] . *Phalaris minor* soil seedbank dynamics. | In prep. [12] |
| Conference paper | Franke, A. C., McRoberts, N., Marshall, G., Malik, R. K., Singh, S., Nehra, A. S. [2002]. Seed longevity and emergence of *Phalaris minor* as affected by tillage regime and herbicide resistance. *Paper for International Conference on Herbicide Resistance Management and Zero Tillage in Rice-Wheat Cropping System*, *4-6 March 2002, CCS Haryana Agricultural University, Hisar, India,* p.35-40 | Published [13] |
| Conference Paper | Franke, A. C., McRoberts, N., Marshall, G., Malik, R. K., Singh, S., Nehra, A. S. and Gill, G. S. [2001]. The contribution of zero tillage for the management of *Phalaris minor* in the Indian rice-wheat system. *Brighton Crop Protection Conference 2001 – Weeds.* pp. 901-906. | Published [14] |

| | | |
|---|---|---|
| Abstract | Malik, R. K. [2000]. Success of zero-till and *Phalaris* management in Haryana. *Third International Weed Science Congress. Brazil, 6-11 June 2000*, **abstract 501**, pp. 241-242. | Published [15] |
| Abstract | Franke, A. C., McRoberts, N., and Marshall, G. [2000]. A population model for *Phalaris minor* Retz., applied for Indian rice-wheat rotations. *WSSA Abstract, 2000 Meeting of the Weed Science Society of America*, **vol. 40**, p.50-51. | Published [16] |

## Activity 3: Programme of Education and Technology Transfer

| **Reference Type** | **Citation Details** | **In prep/ submitted/ published** |
|---|---|---|
| Workshop manual | Franke, A. C., McRoberts, N., Marshall, G. [1999]. Multivariate data analysis in weed science. *Workshop manual for Workshop on multivariate data analysis, Haryana Agricultural University, Hisar, India, 13-15 December 1999.* | Published [17] |
| Workshop manual | Franke, A. C., McRoberts, N., Marshall, G. [2000]. Simulation of ecological processes. *Workshop manual for Workshop on mathematical modelling, Haryana Agricultural University, Hisar, India, 11-14 December 2000.* | Published [18] |
| Workshop manual | Franke, A. C., McRoberts, N., Marshall, G. [2002]. Utility of DFID-funded research for control of *Phalaris minor. Workshop manual for Review Workshop on the utility of socio-economic and lifecycle research for the control of Phalaris minor, Haryana Agricultural University, Hisar, India*, *18-20 March 2002.* | Published [19] |

## Activity 4: Genetic Assessment of *Phalaris minor*

| **Reference Type** | **Citation Details** | **In prep/ submitted/ published** |
|---|---|---|
| Peer-reviewed paper | Marshall, G., Sinclair, W., McRoberts, N., Franke, A. C., Saharan, R. P. and Malik, R. K. [2001]. A genetic assessment of *Phalaris minor. For submission to Weed Research.* | In prep. [20] |
| Abstract | Marshall, G., Sinclair, W., McRoberts, N., Franke, A. C. Singh, S., Saharan, R. P. and Malik, R. K. [2001]. Characterising populations of *Phalaris minor* Retz. via molecular techniques. *2001 Meeting of the Weed Science Society of America, North Carolina, February 2001*, **abstract 120.** | Published [21] |
| Internal report | McPherson, A., Sinclair, B. [2000]. DNA extraction and PCR amplifications of *Phalaris minor*. *Initial Progress Report, Plant & Crop Science Division, Scottish Agricultural College, Auchincruive.* | Published [22] |

# Contribution of Outputs to Developmental Impact

DFID Goal: Yield improved and sustainability enhanced in high potential cropping systems by cost-effective reduction in losses due to pests. Context: Sustainable Livelihoods.

This section will outline the characteristics of the project outputs which contributed to the specific DFID goal and context cited above.

## Farmer-focused Research

In this programme of work, a very significant emphasis was placed upon interacting in a practical way with the farming community. The ecosystem audits resulted in over 220 farmers being interviewed and gained important perceptions into their *Phalaris* problems. Thus while the socio-economic outputs *per se* are valuable, an important appreciation of the evolving nature of the *Phalaris* problem was revealed to inform future research and technology transfer programmes.

The survey information also provided a key means of working with one of the primary extension agencies, via HAU staff. Furthermore, the DFID research operated in concert with existing Indian, World Bank and Australian Government-funded research programmes. Thus collective efforts to secure blueprints for minimising the impact of *P. minor* in wheat/rice ecosystems were ‘academically inclusive’, but delivered locally to the farm end-users.

## Responsive and Participative

As outlined above, a hallmark of the work programme was gaining participation from farmers and HAU academics alike. The importance of this approach was exemplified in the way project outputs were informed by local demand. For example, developing our understanding of the weed life cycle allowed field research around Haryana to be undertaken. However, the utility and value of the experiments were used to impart new skills in data handling and mathematical modelling for the benefit of Indian researchers. This participative research generated local enthusiasm for the disciplines, but exploited in very practical ways. For example, testing different crop management treatments for their economic impact upon wheat production. Thus practical, locally validated ‘tools’ could be used by HAU scientists for extension purposes and the benefit of farmers.

## Multi-level Approach

Minimising the losses attributed to *P. minor* in wheat/rice ecosystems involves a wide range of disciplines. In this project we have produced outputs from holistic, ecosystem audits, technical field and laboratory studies assessing crop losses, weed population dynamics and molecular ecology, plus staff training workshops. The broad range of disciplines have been focused upon the principal target weed, *P. minor*, providing a comprehensive understanding of its socio-economic and agronomic impact upon crop production. In addition, the DFID-funded work has benefited from collaboration with the Indian and Australian research programmes.

A summary of the project contributions are described in Table 4.

**TABLE 4 A summary of the research activities, outputs and contributions towards minimising the socio-economic impact of *P. minor* in wheat/rice ecosystems**

DFID Goal: Yield improved and sustainability enhanced in high potential cropping systems by cost-effective reduction in losses due to pests. Context: Sustainable Livelihoods.

| Research Activity | Outputs | Inputs via Education/ Technology Transfer | Contribution |
|---|---|---|---|
| **Ecosystem Audit** | Identification of economic constraints | Survey approaches[19]<br>Data handling | Characterises the obstacles to profitable wheat production[1,3,4,5] |
| | Socio-economic characterisation of farmers | Multivariate analyses[17] | Describes criteria related to socio-economically successful and disadvantaged farmers[1,2,3,5] |
| | Identification of farmers in the information poverty gap | | Identifies research, technology transfer and extension needs for farmers[1,2,3,5,7,8] |
| **Weed Life Cycle Studies** | Seed longevity characterisation | Data handling | Informs crop rotation/weed management practices and modelling scenarios[3,9,12,13,14,15,16] |
| | Weed seed management<br>➢ burial<br>➢ tillage<br>➢ straw treatment | Data handling<br>Analytical modelling | Provides guidance on best cropping/agronomic techniques designed to minimise crop losses from *P. minor*[3,12,13,14,15,16] |
| | Population Flux<br>➢ tillage effects<br>➢ herbicide effects<br>➢ reproduction of weed/competition | Seedbank assessment<br>Data handling | Contributes quantitative information on the growth and competitive behaviour of *P. minor* in wheat[3,12,13,14]<br>Informs economic loss models |
| | Modelling<br>➢ life cycle<br>➢ population density<br>➢ tillage influence | Simulation modelling[18,19] | Integrates biological understanding and management/economic impacts of *P. minor* in a wide range of cropping scenarios[3,12,16] |
| **Molecular Ecology** | Reproductive biology<br>Evolution of weed biotypes<br>Management | Molecular techniques<br>Data handling | Informs sustainable crop management programmes and instructs on the avoidance of herbicide resistant biotypes of *P. minor*[21,20]<br>New molecular techniques[22] |

Published outputs cited as [1-22]

# Promotion Pathways/Follow Up Action

## Regional Issues

Essentially, in this project the outputs were produced by the SAC/HAU team and shared with participating farmers, extension scientists and research scientists in Hisar. In addition, specific workshops gained involvement from participants in Punjab, Uttar Pradesh, Uttaranchal and Tamil Nadu. The process of promoting the research themes was made throughout the 3 years rather than simply at the end. This evolutionary approach was beneficial since the project work gained exposure to the various end users over a 3 year period. The lessons learned in 'good practice' in terms of crop agronomy, weed management, scientific training, surveying and participative farm-based research are frequently adopted by the HAU staff.

In Hisar, the research and extension programme on *Phalaris* control in the rice/wheat ecosystem is continuing. Funding is still available from National, Australian Government and World Bank sources to progress refinements in cultivation practice, herbicide selection and management advice. The emphasis of the research programme at HAU will probably move towards the rice crop in future.

On the basis of our project, we would suggest that there would be value in undertaking research to further assist the sector of Indian farmers we described as being in the 'information poverty gap'. Essentially, these are the farmers who, for various reasons, become excluded from technological progress via new practices such as zero-till farming. This significant minority are vulnerable to being excluded from successful cropping if a range of alternate, low-tech solutions cannot be found to assist them.

Reaching those in the information poverty gap would require a special understanding of their needs and perceptions. It could be instructive to assess a range of extension techniques to understand how best to communicate and inform these more introvert groups. We would anticipate that such a programme of work could usefully be pursued in a collaborative manner with other potentially 'technologically excluded' groups.

## National Issues

There is a continuing benefit from the programme of work, certainly in Hisar and Punjab. We would anticipate that some of the refereed publications would engender further interest in the programme in India beyond Hisar. In particular, we consider that there is a need to identify a mechanism whereby other Indian agronomists/weed scientists could more readily interact with the HAU programme. At present our perception is that International funding programmes could work more effectively with Indian R&D programmes if Indian research was more collaborative in its domestic strategy. Similarly, International programmes could benefit greatly if domestic research priorities were clearly articulated. Thus in our experience with an Indian/Australian/DFID funded programme, scaling up of such collaborative ventures could be beneficial in reaching a greater number of end users.

An advantage of scaling up is that universities situated in the poorer parts of India [on the Indo-Gangetic plains these are: eastern Uttar Pradesh, Madya Pradesh and Bihar] could benefit from the experience and knowledge collected by universities in States such as Haryana and Punjab, where agriculture is better developed.

# Literature

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Singh, S., Malik, R. K & Ram, M. [1999]. Effect of rice straw burning on the efficacy of herbicides in wheat [*Triticum aestivum*]. *Indian Journal of Agronomy* **44**[2]: 361-366.

Yadav, A., Malik, R. K., Chauhan, B. S. & Gill, G. [2002]. Present status of herbicide resistance in Haryana. *Paper for international workshop on herbicide resistance management and zero tillage in rice-wheat cropping system, 4-6 March 2002, Department of Agronomy, CCS Haryana Agricultural University, Hisar, India*, pp.15-22.

Zhivotovsky, L. A. [1999]. Estimating population structure in diploids with multilocus dominant DNA markers. *Molecular Ecology*, **8**: 907-913.

**FIGURE 1 Scatter plot of Principal Components 1 and 3 for farmers from different regions after Principal Components Analysis, plotted over a map of Haryana**

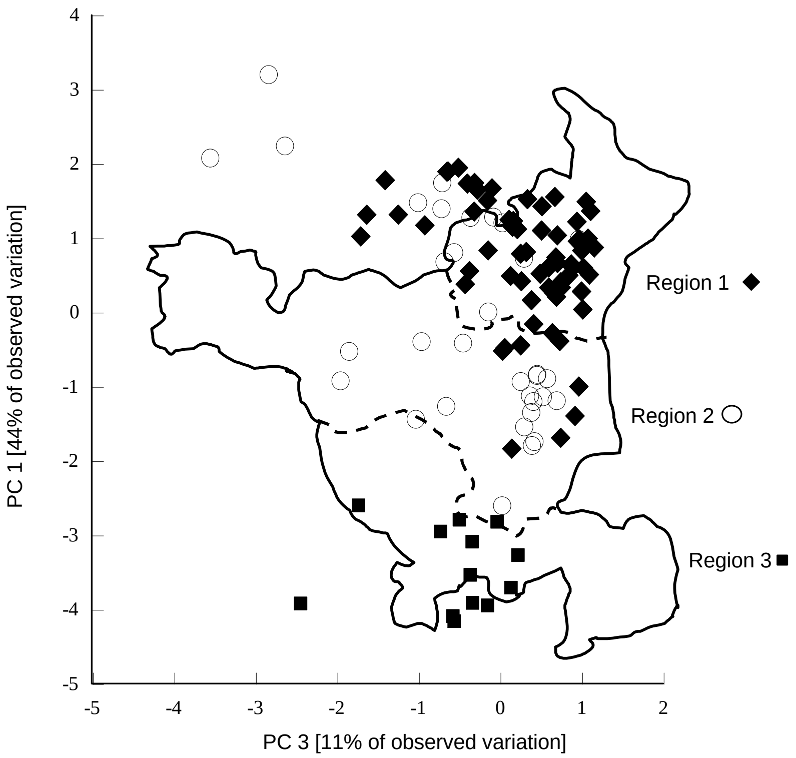



**FIGURE 2 Relation between farm profitability and *P. minor* density, herbicide costs and farmers' rating of the severity of *P. minor* compared with other constraints during wheat cultivation**

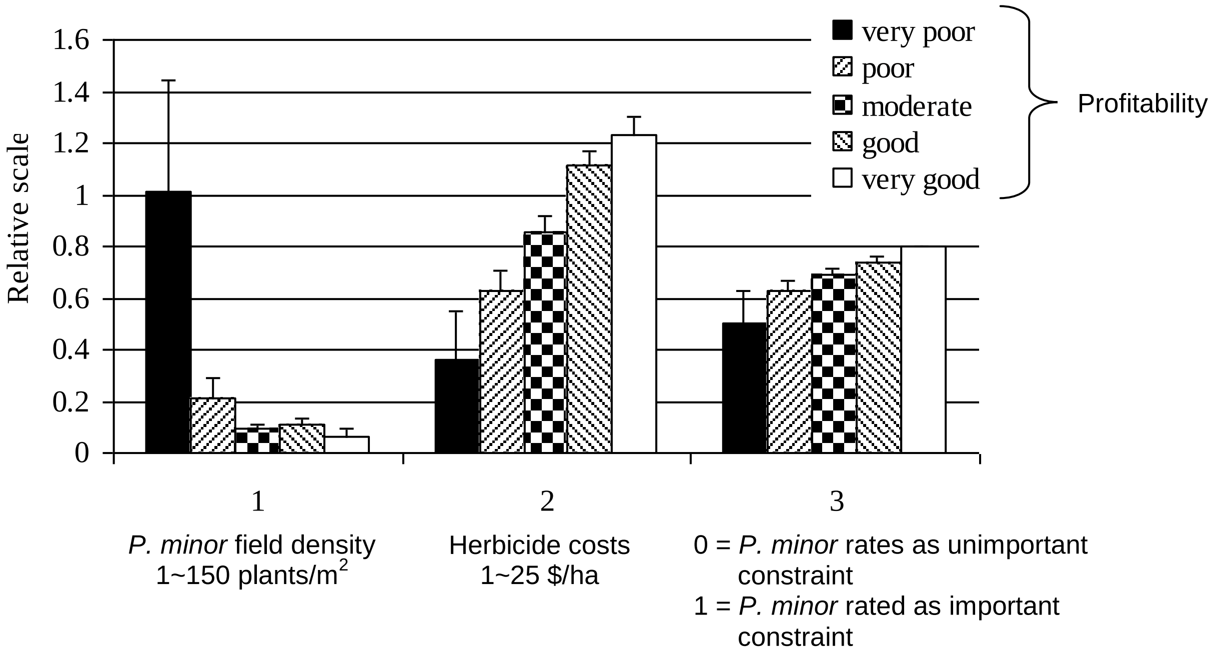


**FIGURE 3 Effect of various ploughing techniques before wheat sowing on the relative vertical distribution of *P. minor* seeds in a millet-wheat rotation**

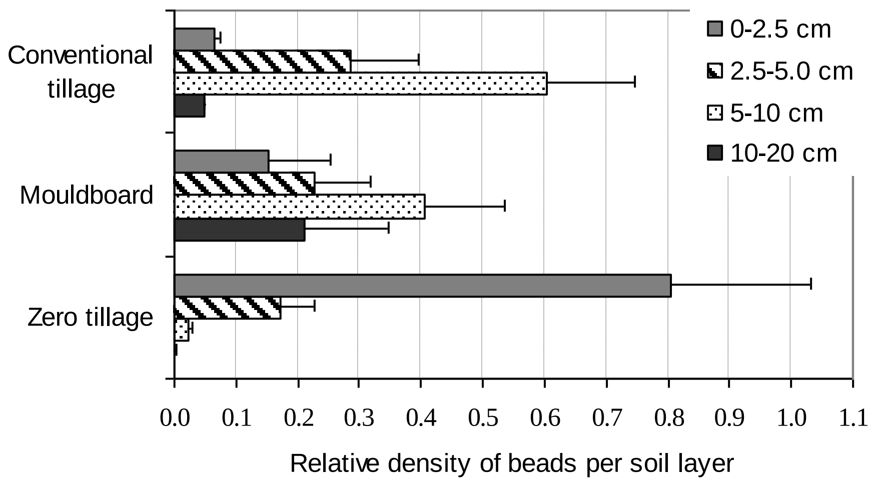



**FIGURE 4 Effect of straw burning on the germinability of *P. minor* seeds of two biotypes buried at various depths**

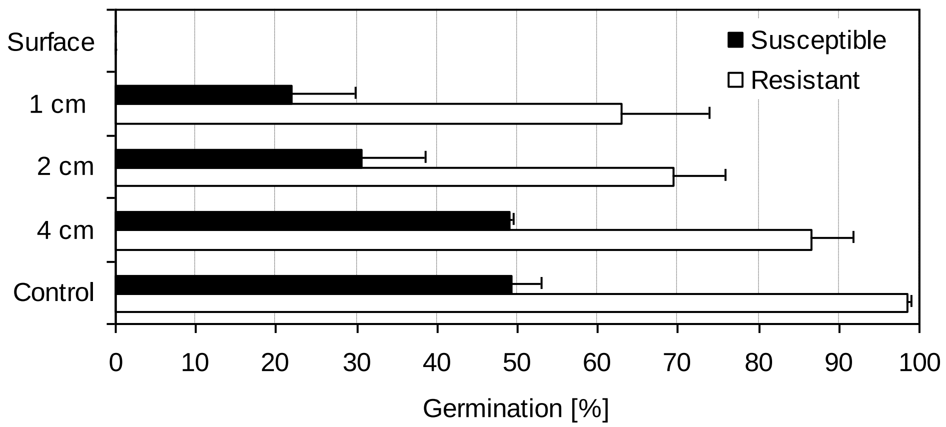


**FIGURE 5 Relationship between *P. minor* soil seed density and emerged seedling density for conventional and zero-tillage [season 2001-02]**

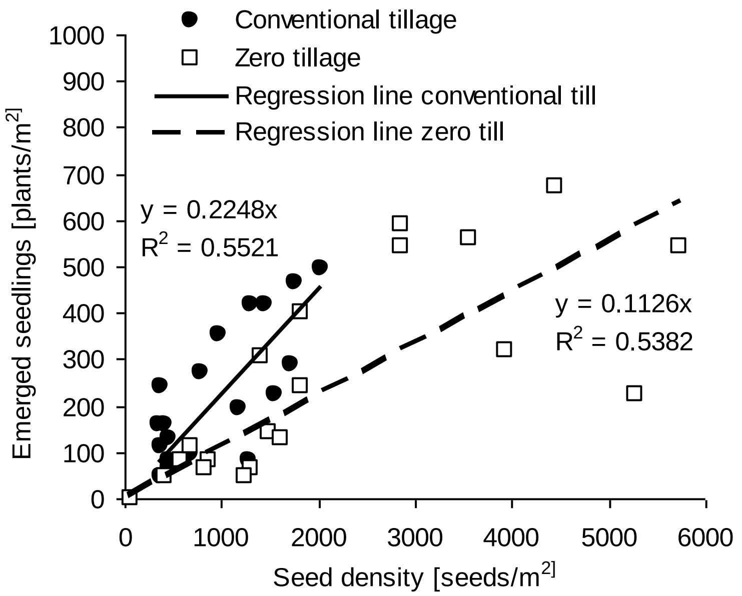
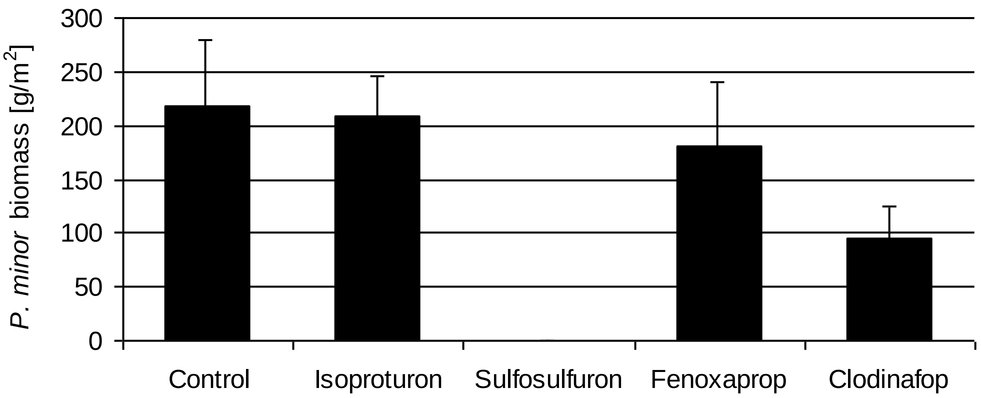



**FIGURE 6a&b Effect of herbicide treatments of *P. minor* biomass and density at final harvest [season 2001-02]**

**[a]**




**[b]**

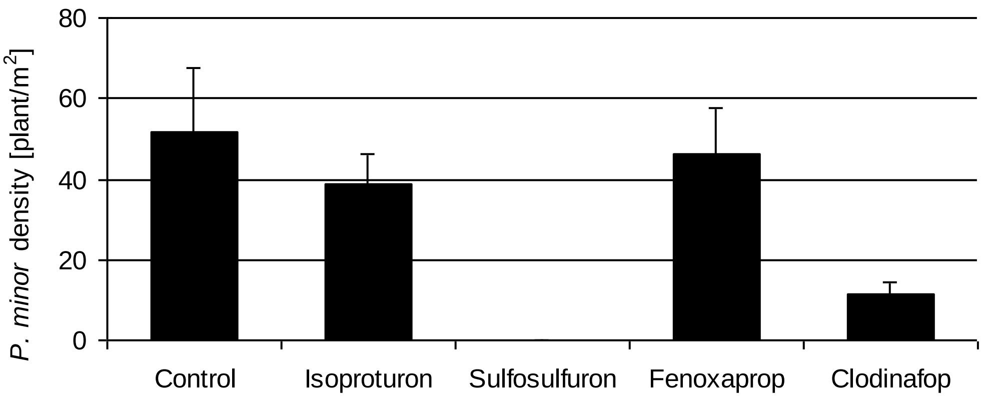
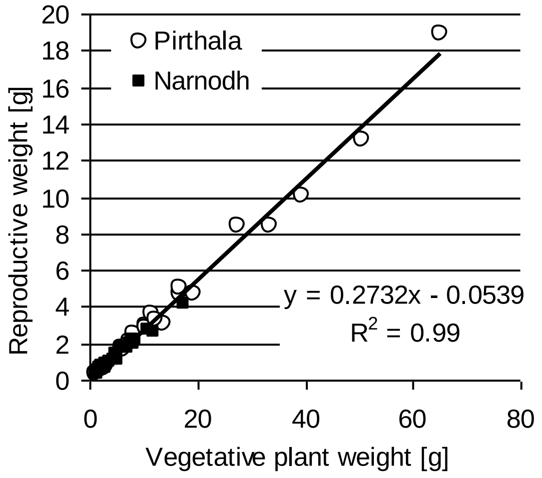


**FIGURE 7a&b Relationship between *P. minor* vegetative plant weight and reproductive weight [a] and 1000-seed weight [b]**

[a]




[b]

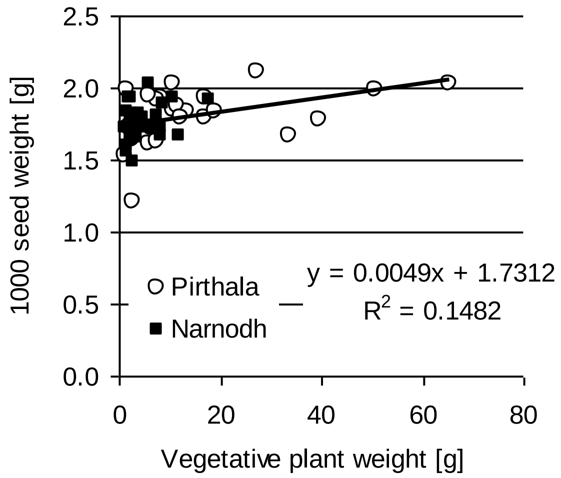



**FIGURE 8 Scatter plot of 118 *P. minor* individuals in two principal axes after PCO of a similarity matrix constructed from marker data. Plants were assessed from four field sites in Haryana**

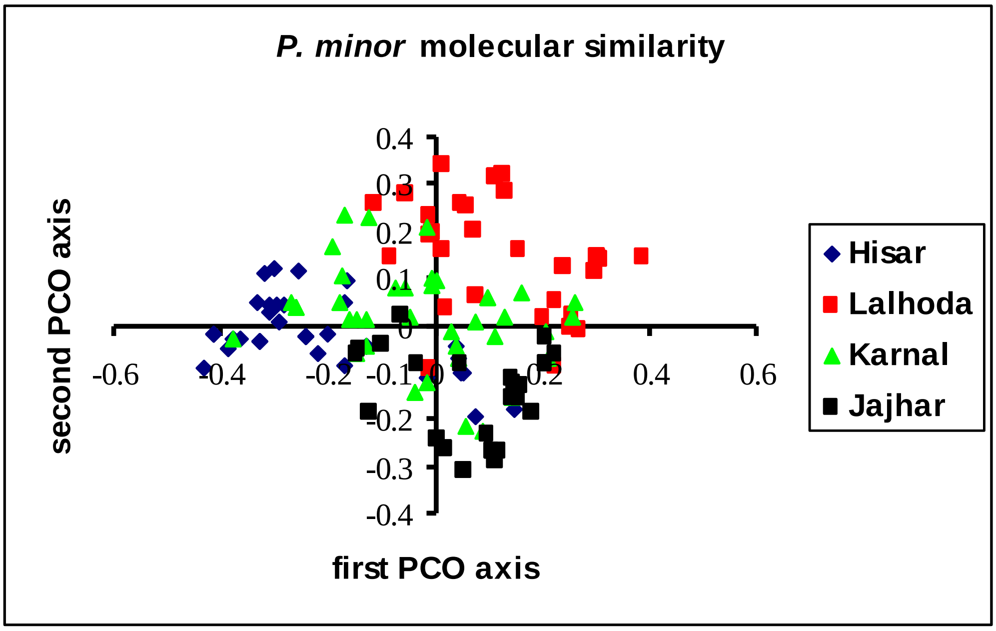


**FIGURE 9 Flowchart illustrating the lifecycle of *Phalaris minor* in the Indian rice-wheat rotation. Solid lines indicate the lifecycle, broken lines indicate processes influencing the flow**

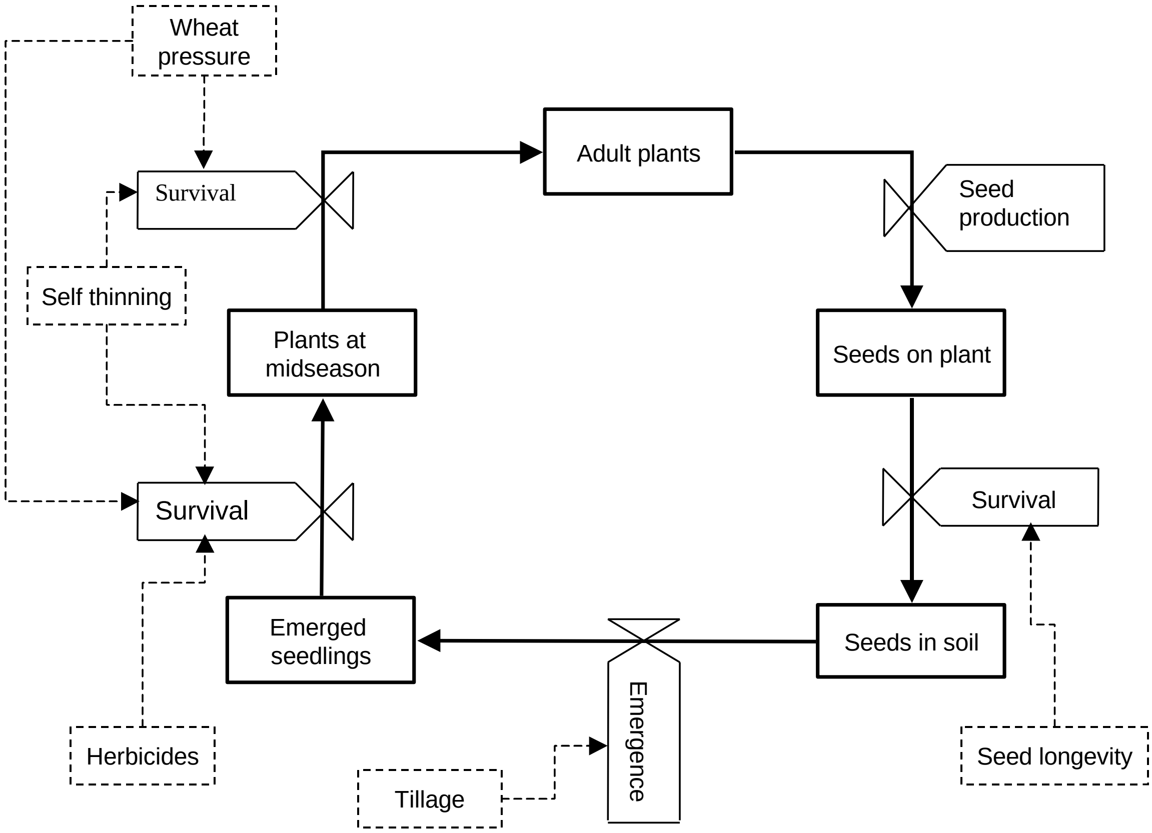



**FIGURE 10a A representative early simulation prior to model calibration**

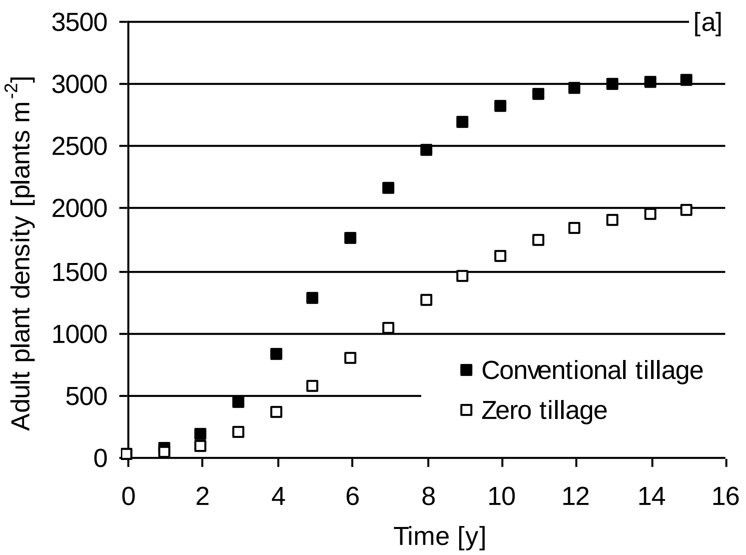


**FIGURE 10b Simulated *P. minor* population densities under different control strategies [calibrated model]**

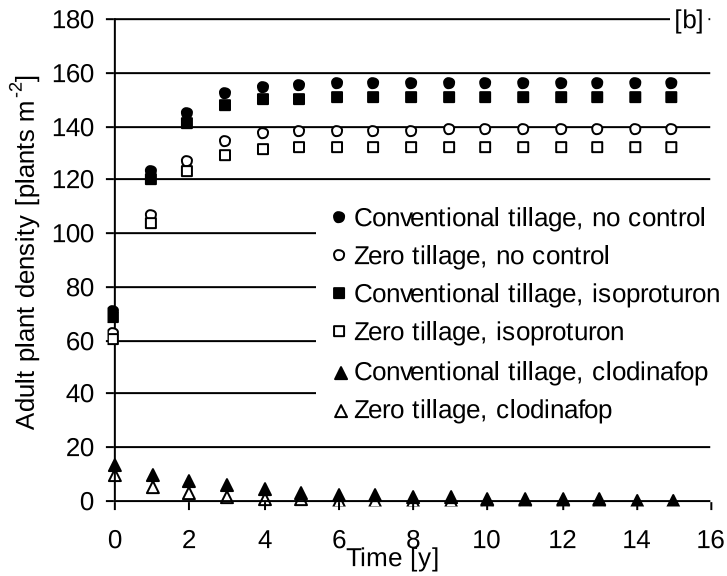



**FIGURE 10c Combined effect of zero tillage and alternating crop on *P. minor* density**