TITLE: ECOLOGICAL AND SOCIOLOGICAL ASPECTS OF THE *PHALARIS MINOR* EPIDEMIC IN THE RICE-WHEAT SYSTEM OF HARYANA, INDIA

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PhD thesis

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Declaration

This thesis has been composed by myself and has not been presented in any previous application for a degree. The work, of which this is a record has been done by me unless otherwise stated and all sources of information have been specifically acknowledged by means of references.

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FOREWORD

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A shortened version of Chapter 5 has been accepted for publication by the journal *Experimental Agriculture* under the title of 'A survey of *Phalaris minor* in the Indian rice-wheat system' [Franke *et al.*, 2003]. A slightly modified version of chapter 6 has been submitted for publication to the *Oxford Journal of Development Studies* under the title of 'New approaches to modelling the adoption of agricultural innovation in structured populations.' A paper on *Phalaris minor* seedbank studies (Chapter 2 and 3) is in preparation for submission to the journal Weed Science. A paper for the Brighton Crop Protection Conference on zero tillage and *P. minor* management has been published by Franke *et al.* [2001].

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LIST OF ABBREVIATIONS

a.i.	active ingredient
ANOVA	Analysis of Variance
CVA	Canonical Variate Analysis
DAS	Days After Sowing
DFID	UK Department for International Development
FCM	Fuzzy Cognitive Map
FST	Fortran Simulation Translator
FYM	Farmyard Manure
HAU	Haryana Agricultural University
IPU	Isoproturon
LIP	Lloyd's Index of Patchiness
LSD	Least Significant Differences of mean
PCA	Principal Components Analysis
SAC	Scottish Agricultural College
SE	Standard Error for means

ABSTRACT

The fertile Indo-Gangetic plains of northern India are well suited for intensive crop production systems and provide food grains to millions of people living on the Indian subcontinent. The prevalent agro-ecological circumstances in the rice-wheat system of the Indo-Gangetic plains allowed *Phalaris minor* to become a ubiquitous weed infesting around 16m hectares of wheat, and causing yield losses up to 80%. The weed has hitherto been controlled by the phenyl-urea herbicide isoproturon, but the development of herbicide resistance among *P. minor* biotypes in the early 1990s drastically reduced control. Since then, newly introduced herbicides have relieved the weed pressure. However, the continuing risk that *P. minor* biotypes develop cross-resistance against other herbicides stresses the need for an integrated weed management strategy for the region.

The present thesis addressed ecological and wider socio-economic aspects of the *P. minor* epidemic in the rice-wheat system of Haryana State in northwest India. Three types of complementary field studies have been conducted: (1) studies of the soil seedbank dynamics of *P. minor*, (2) research on the lifecycle of *P. minor* as affected by tillage regime and herbicides and (3) a farmer survey concerned with the wider agronomic and socio-economic impacts of the *P. minor* epidemic. A population dynamics model of *P. minor* in competition with wheat was developed to organise and integrate existing knowledge of biology and ecology of *P .minor* with new experimental observations made in the current study. The model was used to test alternative weed control strategies. A second modelling study, of the effect of aggregation among farmers on the adoption rate of technological innovations, aimed to provide novel techniques to incorporate heterogeneity in societies into quantitative models of adoption processes.

Soil seedbank studies showed that *P. minor* seed half-life time is often limited to less than one year. Location and depth of burial were among the factors that affected seed longevity and

longest seed longevity was observed when seeds were buried under anaerobic soil conditions at 30cm depth. Studies on the effect of soil cultivations on the vertical movement of seeds throughout the soil profile suggested that the practice of mouldboard ploughing before wheat sowing may assist in curbing *P. minor* populations by moving seeds to depths from which they cannot emerge. Straw burning was found to have a strong impact on the survival of seeds lying on the soil surface, while seeds covered with soil and slightly protected from strong heat usually survived straw burning. The results highlighted the importance of soil seedbank processes for *P. minor*'s entire population dynamics.

Lifecycle studies have revealed that application of zero tillage systems reduces *P. minor* pressure by diminishing the emergence rate of first and second flush seedlings. Herbicide applications suggested that isoproturon-resistant *P. minor* biotypes exhibit cross-resistance against the newly introduced herbicide fenoxaprop-P-ethyl. A strong linear relationship was found between *P. minor* vegetative weight and reproductive output. The data suggested that large seed losses occur between the stage of seeds on the mother plant and the soil seedbank at the beginning of the following growing season. The lifecycle model assigned an important role to zero tillage in curbing *P. minor* populations when herbicide inputs are low. The model also suggested that *P. minor* can be controlled effectively without the use of herbicides provided that 50% of land is used for winter crops other than wheat each season. It is concluded that crop diversification should have a central place in the development of an integrated weed control strategy to reduce reliance on herbicide for weed control.

The socio-economic survey 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 may lead to a widening gap in adoption levels of technology and socio-economic strength between farmer classes in the future, which may ultimately result in expulsion of many small farmers out of farming. While the resulting consolidation of farming might be advantageous for the business at a macro-economic scale, the social consequences of disappearing rural livelihoods may be grave. This can be avoided by making innovative technologies available to small-scale farmers. As small farmers are likely to remain a significant feature of farming in Haryana in the near future, improving the accessibility of higher technologies to smaller farmers would enhance the general level of technology adoption in Haryana. This in turn, may provide opportunities to diversify the present cropping pattern, benefiting *P. minor* control as well as the entire sustainability of the farming system in Haryana.

CHAPTER 1: STUDY OF LITERATURE

1.1 *Phalaris minor* in Haryana

1.1.1 Farming in Haryana

Haryana is a relatively small state of 44 thousand km^2 on the fertile Indo-Gangetic plains of northern India [Figure 1.1]. The Indo-Gangetic plains, with their fertile, alluvial soils and well-developed irrigation systems, are a region of special utility for intensive cropping systems, such as rice-wheat. In total, this region of 69m ha is capable of producing 150mt of wheat and 100mt of rice per annum. Highest yields on the plains are harvested in Haryana and neighbouring Punjab which are among the richest states of India, mainly due to a flourishing farming sector. Haryana and Punjab are known as India's breadbasket.

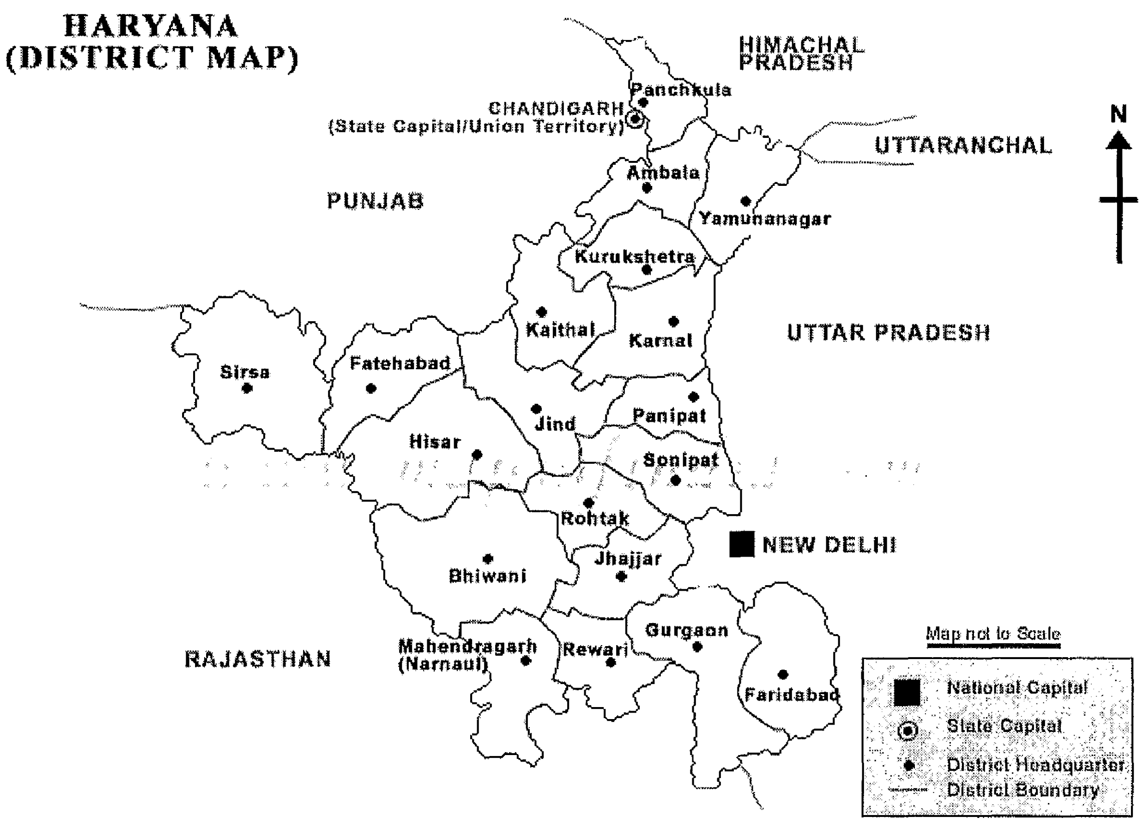


Figure 1.1 District map of Haryana [Mapsofindia, 2002].

Climatically and edaphically, Haryana shows large variations. At the southwest border with Rajasthan, soils are light and sandy, while in the northeast the dominant soil type is silty clay loam. The climate at the southwest border is semi-arid with an average rainfall of 300mm, whereas the climate in the northeast is subtropical with rainfall between 750 and 1500mm [Figure 1.2] [Singh *et al.*, 1985]. Most precipitation falls during the monsoon, from mid June until the end of September, while average monthly rainfall outside the monsoon season is typically less than 20mm. The coolest month in Haryana is January with an average day temperatures around 14^0C and a minimum recorded temperature of 1^0C. Hottest months are May-June with average day temperatures around 36^0C and a maximum recorded temperature of 48^0C.

In 1990-1991, average landholding in Haryana was 2.43ha, which was above India's national average of 1.57. Like in the whole of India, land is unequally divided among farmers in Haryana; 41% of the farmers owned less than 1ha and had access to 8% of the total available arable land, while 51% of the available land was in hands of 12% of the largest farmers [Anonymous, 1996]. There are no reasons to assume these figures have changed much since 1990-91.

On roughly half the land area of Haryana, where sufficient rainfall and irrigation facilities are available, rice-wheat is the dominant rotation. World wide, rice-wheat is grown in sequence in the same year on an area of 26m ha, mostly in India, China, Pakistan, Nepal and Bangladesh [Timsina & Connor, 2001]. Wheat is grown in winter (October-April), followed by one or two rice cultivations in summer (May-October). Some Haryana farmers in the rice-wheat belt alternate rice-wheat with a two-year sugarcane crop. In the drier areas with lighter soils, wheat is also the dominant winter crop, while rice is often replaced by cotton, pulses, pearl millet (*Pennisetum americanum*) or vegetables. Various winter crops besides wheat are being cultivated. Farmers involved in dairy production often cultivate berseem (*Trifolium alexandrium*) on small plots as cattle fodder. Other alternatives for wheat include potato, sugarcane, chickpea, cluster bean (*Cyamopsis tetragonoloba*), mustard seed (often in a mixtures with wheat), sunflower seed and vegetables, such as tomato, cucumber, pepper, chilli, eggplant, cauliflower and watermelon. However, low profitability, poor market infrastructure and large price fluctuations limit the production area of alternative winter crops. Cultivating wheat ensures farmers a relatively secure net return. The government stimulates farmers to grow rice-wheat by providing them guaranteed minimum support prices and storage facilities for these food grains, while prices for most other agricultural products are market-determined. Accordingly, wheat is the dominant winter crop raised on an estimated 80% of the arable land in Haryana. Potential wheat yield in Haryana is one of the highest in India and has been estimated 7-8t ha^{-1} [Agarwal, 1993]

In Haryana, the success of both rice and wheat cultivations depend heavily on the availability of sufficient additional irrigation water. Generally, in the wet northeast, groundwater is easily accessible and of sufficient quality to be used as irrigation water. In the drier southern regions, deep groundwater levels and poor quality of the groundwater force farmers to use canal water for irrigation. In total, 36% of the state's groundwater is too brackish for irrigation [Singh *et al.*, 1985]. Overexploitation of groundwater for irrigation purposes has resulted in considerable lowering of groundwater tables, while excessive irrigation through canal water has allowed salty groundwater from deeper layers to reach the soil surface, which has reduced the productivity of the land in some parts of Haryana [Singh & Singh, 1995].

Overexploitation of water resources and land degradation due to salination are considered among the main long-term threats for sustaining the present high productivity of the rice-wheat system on the Indo-Gangetic plains [Abrol, 1999; Gupta & Abrol, 2000]. Other threats to the long-term sustainability of the rice-wheat system include depletion of soil macro-nutrients, such as phosphate and potash, micro-nutrients, such as magnesium, zinc and copper, and a decline in the soil organic carbon contents due to a reduced use of organic fertilisers [Fujisaka *et al.*, 1994; Yadav *et al.*, 2000]. Build-up of insects, weeds and diseases in the rice-wheat system is another concern for its sustainability, as demonstrated clearly by the present *Phalaris minor* epidemic.

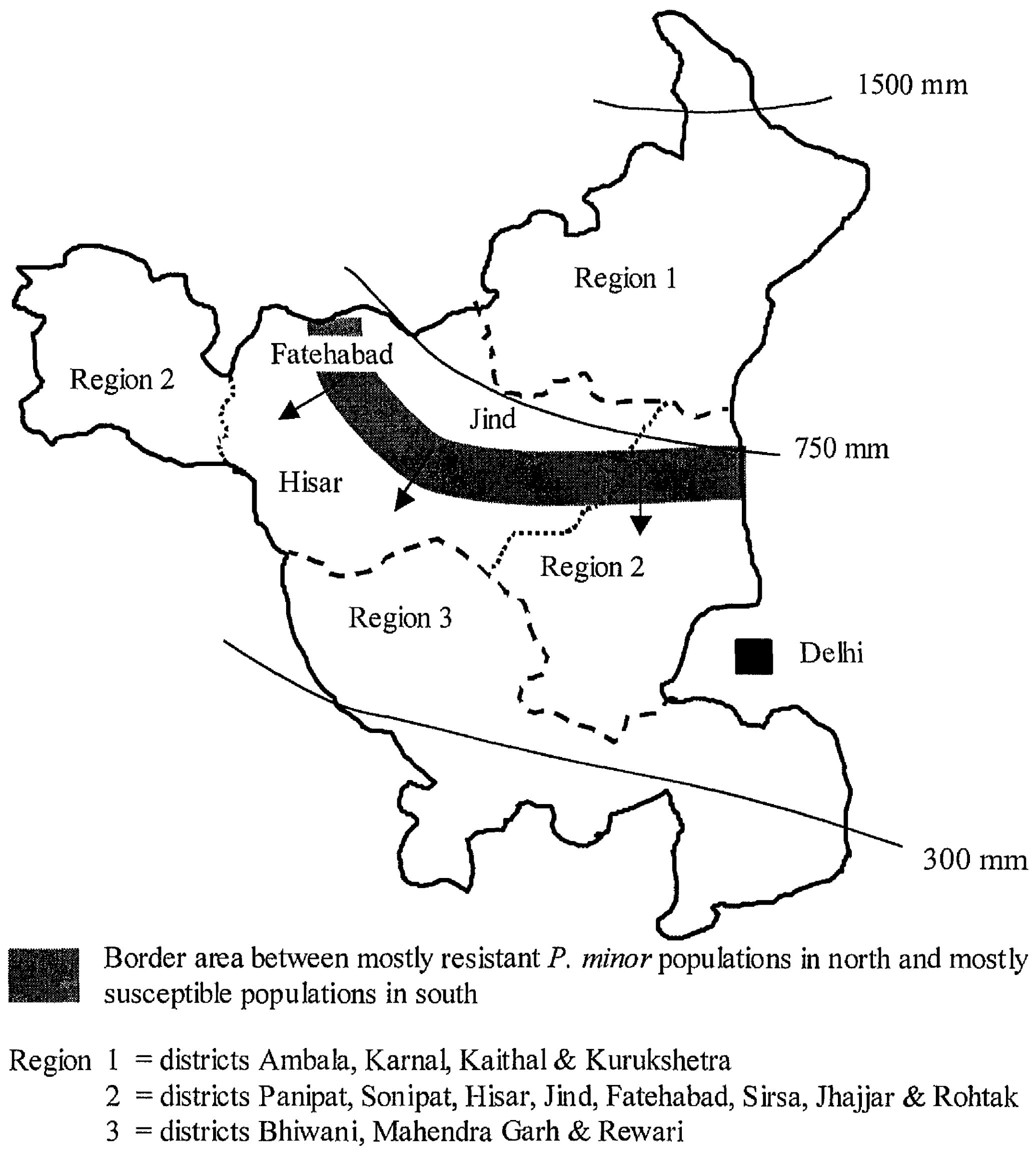


Figure 1.2 Map of Haryana indicating annual rainfall and geographic distribution of resistant *P. minor* biotypes.

1.1.2 **Phalaris minor** *and the development of herbicide resistance*

Phalaris minor emerged in wheat in northern India at the beginning of the Green Revolution in the early 1970s. In this period, the introduction of irrigation systems, chemical fertilisers and herbicides allowed farmers to apply an intensive rice-wheat rotation. New dwarf-sized varieties of rice and wheat tremendously increased the potential and actual yields. As a result, wheat production in India increased between 1970 and 1999 by 252% [FAOSTAT, 2001]. The introduction of irrigation systems, chemical fertilisers and short-strawed wheat varieties greatly changed the agro-ecological circumstances for weeds.

It is uncertain whether *P. minor* reached the Indo-Gangetic plains through the import of Mexican wheat varieties in the late 1960s or the weed had been present on the plains for longer. It was only during the Green Revolution that *P. minor* developed into a major production constraint for wheat. It flourished in the fertile and humid soil conditions brought by the green revolution [Prasad *et al.*, 1993; Walia & Gill, 1985], while the dwarf wheat varieties had low weed-suppressing abilities [Paul & Gill, 1979; Brar & Singh, 1997]. *P. minor* seed production is high and seeds are so small that they can easily disperse to new areas through contaminated crop seeds, machinery, wind or irrigation water [Yaduraju, 1999]. Consequently, *P. minor* became a ubiquitous weed infesting more than 16m ha of wheat in northern India.

Until recently, the phenylurea herbicide isoproturon (IPU) was an inexpensive and, if correctly applied, effective tool to control *P. minor* and soon after its introduction in 1977 farmers widely adopted the herbicide. Continuous use of IPU for more than 15 years resulted in the development of IPU-resistant biotypes in Haryana, Punjab and Uttar Pradesh. Incorrect application techniques and cost-saving low herbicide doses accelerated the development of resistance. In Haryana, the first case of resistance was reported in district Fatehabad in 1991. Soon after, resistant biotypes were found in districts Karnal, Kaithal and Kurukshetra as well. Initially, resistant biotypes were mostly found on farms practising a rice-wheat rotation for more than 8 years [Malik, 1995]. Subsequently, resistant *P. minor* infested other rotations, such as cotton-wheat, in the drier central regions of Haryana as well [Figure 1.2]. Yaduraju [1999] estimated that in 1999 between 0.8 and 1m ha of wheat in Haryana was infested by herbicide resistant *P. minor*, although no systematic survey has been made. In pot experiments comparing IPU susceptible and resistant *P. minor* populations, without the use of herbicides, no reduction in fitness in terms of germination and growth habits has been observed [Chhokar, 1998], explaining the aggressive population dynamics of resistant populations. Resistant biotypes require 2 to 18 times higher doses of IPU for the same level of control than susceptible populations [Malik & Singh, 1995; Singh *et al.*, 1997; Walia, *et al.*, 1997; Malik *et al.*, 1998; Kulshrestha *et al.*, 1999]. At such high levels, the herbicide shows phyto-toxicity to wheat.

In 1991, when resistance was reported for the first time, no direct solution was available for the failing control of herbicide-resistant *P. minor.* Farmers hit by resistance faced complete crop failure and wheat fields were frequently ploughed up or harvested as fodder. Farmers abandoned wheat and started growing alternative winter crops. Yearly growth in wheat production stagnated in Haryana, while the country's annual population growth rate remained 1.8% [FAOSTAT, 2001]. India's self-sufficiency in wheat production was placed at risk and the epidemic was described as a major economic event in India [Singh *et al.*, 1999].

Since 1998, three new herbicides for the control of *P. minor*, sulfosulfuron, fenoxaprop-P-ethyl and clodinafop-propargyl, have been brought on the Indian herbicide market. These herbicides achieve, under experimental conditions, almost 100% control of *P. minor* without phyto-toxicity to wheat [Walia & Brar, 1996; Brar & Singh, 1997; Brar *et al.*, 1999]. Since the introduction of the new herbicides the control of resistant *P. minor* in the areas hit by resistance has drastically improved. However, relatively high prices for these herbicides and farmers' ignorance about resistance has slowed down the adoption of the new herbicides and consequently, resistant biotypes continue to quickly expand their infestation area.

1.2 Biology and ecology of *Phalaris minor*

1.2.1 Geographic distribution

Phalaris minor (Retz.), littleseed canarygrass, is an annual grass belonging to the family of the Gramineae [Stace, 1991]. The genus *Phalaris* contains, world wide, 22 species. *Phalaris minor* along with *Phalaris paradoxa* and *Phalaris brachystachys* are common weeds in cereals. Except for the poles, *Phalaris minor* is present in every part of the world [Singh *et al.*, 1999a]. It has been recorded as a major weed in wheat in the southern states of the United States, Latin America, the Mediterranean [Afentouli & Eleftherohorinos, 1999], Iran [Mirkamali, 1987] and the Indo-Gangetic plains of the Indian subcontinent. For a world map of the geographical distribution of *P. minor*, see Singh *et al.* [1999a].

Within Haryana, *P. minor* is mostly abundant in the northern part, which is dominated by rice-wheat rotations. This area roughly coincides with the present distribution area of IPU-resistant biotypes in Haryana and continues in Punjab, Uttar Pradesh and Uttaranchal. Towards the southern areas of Haryana with mostly cotton-wheat, millet-wheat and pulse-wheat rotations, *P. minor* pressure is less. However, *P. minor* distribution area is moving southwards, as noticed by local farmers, and population pressure is building up in these areas. Also in certain areas of northern Rajasthan, *P. minor* has recently emerged as a major weed in wheat (personal observation).

1.2.2 Dormancy and longevity

P. minor exhibits primary dormancy, which is the dormancy found in freshly shed seeds, as well as secondary dormancy, which is induced when seeds do not germinate after the release of primary dormancy [Karssen, 1982]. Yaduraju *et al.* [1984] and Chhokar [1998] found that at shedding, *P. minor* seeds were unable to germinate and required a minimum period of two months of storage under laboratory conditions until first germination occurred. Only after four months of storage, germination rates under various temperature regimes were approaching those of fully matured 12-month old seed. Singh [1998] reported a primary dormancy of 6 month after shedding. These differences in observed duration of primary dormancy may be attributed to variation in temperatures during storage. Singh & Dhawan [1976] found that recently shed seeds stored at 30^0C lose primary dormancy after three months, while seeds stored at 10 and 0^0C lose dormancy after respectively four and five months of storage, suggesting that the duration of primary dormancy is temperature dependent.

After losing its primary dormancy, *P. minor* seeds germinate when circumstances are favourable, otherwise seeds go into secondary dormancy. Anaerobic conditions, as experienced in the paddy rice fields, are a common cause for the induction of secondary dormancy in the rice-wheat system [Parasher & Singh, 1985]. Under laboratory conditions, *P. minor* seed can be stored without losing its germination capacity up to 4.5 year. Thereafter, seed viability deteriorates and after 8.5 year of storage, seeds lose their capacity to germinate [Chhokar, 1998]. Under field conditions however, seed longevity seems much shorter than under laboratory conditions.

1.2.3 Germination and emergence

Many studies have confirmed that optimum germination temperature for *P. minor* is between 14 and 22^0C [Okereke *et al.*, 1981; Mehra & Gill, 1988; Chhokar & Malik, 1999], while some studies have reported equally good, though slightly delayed germination rates at 10^0C [Bhan & Choudary, 1976; Yaduraju *et al.*, 1984; Jimenez Hidalgo *et al.*, 1993]. There is a sharp decrease in germination when temperatures are above 25^0C and no germination occurs with temperatures above 30^0C or below 5^0C. Optimum germination temperature varies among *P. minor* biotypes, related to soil type [Jimenez-Hidaldo, 1993] and other factors. Dhawan *et al.* [2001] found that isoproturon-resistant biotypes have the ability to germinate at higher temperatures than susceptible biotypes. This could be related to the enhanced activity of cytochrome-P450 enzymes of resistant biotypes [Singh *et al.*, 1999a]. Also seed age may change the temperature range suitable for germination. Singh & Dhawan [1976] reported that freshly shed *P. minor* seeds stored for six months or more have the ability to germinate at a wider temperature range as compared with seeds stored for three to five months.

Jimenez-Hidalgo *et al.* [1993] found a strong stimulating effect of light on *P. minor* germination rate. Seeds under illuminated conditions had an average germination rate of 88%, as compared with 25% for seeds under dark conditions. Yaduraju *et al.* [1984] on the other hand, observed no difference in germination rates between seeds exposed to dark and alternating dark/light conditions and concluded that light had little influence on *P. minor* germination. Seeds with a dark brown seed coat are fully matured and germinate better than light yellow- or green-coated seeds [Mehra & gill, 1988; Chhokar, 1998]. The minimum moisture level required for germination is higher for *P. minor* than for wheat [Chhokar *et al.*, 1999]. At an osmotic potential of –6 bar, *P. minor* has a germination rate of 9%, compared with 64% germination for wheat.

Optimum seeding depth for emergence is 0-5cm. Yaduraju *et al* [1984] reported that under greenhouse conditions seeds on top of the surface show less emergence than those buried at 1-6cm depth. This could be related to an inhibiting effect of strong daylight on the *P. minor*'s germinability. Buried between 5 and 10cm, *P. minor* shows delayed and reduced emergence and below 10cm no emergence occurs at all [Chhokar *et al.*, 1999; Okereke *et al.*, 1993]. Kumar and Kataria [1977] found that in a field where the upper soil horizon is dry, which is common in farmers' fields, *P. minor* seeds from lower moist regions of the profile emerge first, highlighting the importance of sufficient moisture for germination.

1.2.4 Seed production

P. minor seed production is a function of accumulated biomass rather than the number of tillers or panicles. Whereas late-emerging *P. minor* has the tendency to produce more tillers than early-emerging plants, the elongated growing season for early-emerging plants allows them to accumulate more biomass and therefore produce more seeds [Bhan & Choudary, 1976]. The number of seeds per panicle varies between 3 and 460. The maximum observed seed production of a free standing *P. minor* plant is 18 200 seeds [Sat Paul & Gil, 1979]. Seed production in a monoculture of *P. minor* can be as high as 6.12t ha^{-1}. Sat Paul & Gill [1979] reported that in competition with wheat, *P. minor* seed production varies between 200 and 1700 seeds $plant^{-1}$, which is equivalent to 0.25 and 2.1t ha^{-1}. Thousand seed weight varied between 1.4 and 2.2g.

1.2.5 Crop weed interaction

In general, crops and weeds compete with each other for the essential resources for plant growth, *i.e.* light, nutrients and water. Due to the complexity of relationships between morphological and physiological characteristics of species and competitive abilities of these species in mixtures, a mechanistic understanding of crop-weed interactions is often lacking [Kropff & van Laar, 1993]. As this is also true for *P. minor* in wheat, the information given below is limited to a number of studies acknowledging serious competition for nutrients, water and light between *P. minor* and wheat.

P. minor competing with wheat has the potential to take up large amounts of nitrogen and water. Walia & Gill [1985a] reported that *P. minor*, growing in the field in mixtures with wheat, had a potential nitrogen uptake of 25kg ha^{-1}. Furthermore, they found that application of 40kg N ha^{-1}, as compared with 80 and 120kg N ha^{-1}, reduced *P. minor* growth due to nitrogen stress, whereas high application levels of nitrogen (160kg N ha^{-1}) reduced *P. minor* biomass due to increased competitiveness of wheat. Singh *et al.* [1984] and Walia & Gill [1985b] also reported reduced growth of *P. minor* under nitrogen applications of 120 and 160kg ha^{-1}, as compared with lower doses. These results indicate that, in mixtures with wheat at low nitrogen application levels, *P. minor* growth is limited by nitrogen availability, while at higher doses, light or water shortage, resulting from the competitive pressure exerted by the crop, is the limiting growth factor. Khera *et al.* [1995] found an increased water expense and reduced wheat nitrogen use efficiency with increasing densities of *P. minor*. Malik & Singh [1993] reported that water use efficiency of wheat in the presence of 60 *P. minor* plants m^{-2} and 80 broadleaf plants m^{-2} in wheat was reduced from 12.3 to 9.4kg ha^{-1} mm^{-1}, as compared with weed free plots.

Wheat yield reductions due to the competitive pressure of *P. minor* can be very high. Mehra & Gill [1988] reported that wheat yields were reduced by 8 and 44% with increasing *P. minor* densities from 50 to 250 plants m^{-2}. This is in line with findings by Dhaliwal *et al.* [1997] and Khera *et al.* [1995], Malik & Singh [1993] and Balyan & Malik [1989] in Haryana and Punjab and with those of Afentouli & Eleftherohorinos [1996] in Greece. Cudney & Hill [1977] observed a 60% reduction in wheat yield as a result of 765 *P. minor* plants m^{-2} in California (U.S.). Under field conditions in Haryana and Punjab, populations of 200-400 plants m^{-2} at the end of the growing season are common when herbicides have failed [Singh *et al.*, 1999a].

1.2.6 Lifecycle in the rice-wheat system

The lifecycle of *P. minor* is well adapted to the prevailing agro-ecological conditions of the rice-wheat system on the Indo-Gangetic plains and its development rate is highly synchronised with that of wheat. *P. minor* germinates in flushes and the first flush germinates along with wheat after the pre-sowing irrigation, between the end of October and early December [Figure 1.3]. The second flush emerges after the first irrigation, 20-30 days after sowing (DAS), and the third flush emerges after second irrigation, 40-60 DAS. A fourth, fifth and sixth weed flush may emerge after each subsequent irrigation, but these flushes hardly affect the crop-weed interaction and contribute little to the seed rain. Weed emergence during the first and second flush may be very high, up to 3000 seedlings m^{-2} [Yaduraju, 1999]

Herbicides are usually applied when the first weed flush is in its two-leaf stage between 25 and 40 DAS, between early December and late January. Later flushes are less affected by herbicide application than the first flush. Reduced intra-specific competition experienced by later weed flushes as a result of herbicide-induced mortality may benefit their growth. From February until the end of the growing season, farmers, as well as landless people, harvest *P. minor* as fodder for cattle.

P. minor matures and sheds its seeds from mid March until wheat harvest in April. Time of seedling emergence has little influence on *P. minor*'s time of maturation and initiation of seed shed. This indicates that flowering is induced by temperature and/or daylight changes rather than plant biomass or age. Though the majority of the *P. minor* seeds have been shed by the time wheat is harvested , some seeds are harvested along with the wheat and may return to the seedbank when farmers use home-saved seeds in subsequent years.

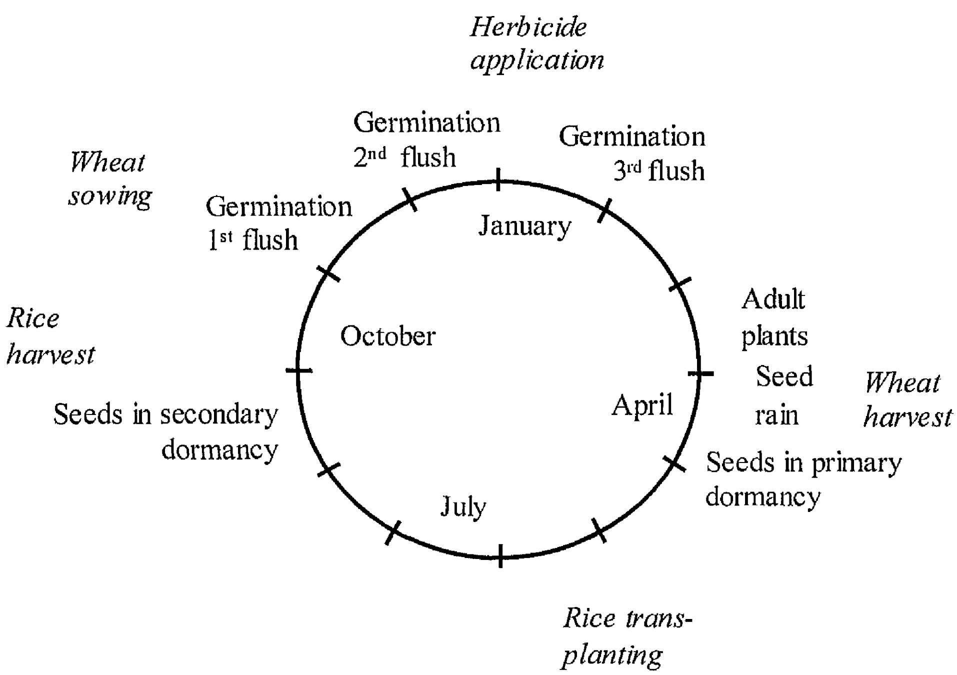


Figure 1.3 Schematic representation of the lifecycle of *Phalaris minor* in the Indian rice-wheat system.

P. minor seeds stay on the soil surface until the soil is cultivated for the following rice crop, usually in May or June. This period, when seeds lay unprotected on the soil surface and are susceptible to predation and straw burning, may be critical for seed survival. Soil cultivations before rice transplanting bury the weed seeds. The anaerobic soil conditions, as experienced in paddy rice, seem to favour *P. minor* seed longevity [Parasher & Singh, 1985]. Freshly shed seeds stay in primary dormancy for around four months. Seed dormancy is broken in autumn when day temperatures drop below 22^0C and circumstances are favourable for germination, otherwise seeds go into secondary dormancy.

1.3 *Phalaris minor* control

1.3.1 Chemical control

Application of herbicides can be seen as an easy way of controlling *P. minor*, because effective herbicide application does not require extensive knowledge on the weed's biology and ecology in its agro-ecosystem and herbicide efficacy can easily be monitored in the field. Therefore, many farmers prefer herbicides to other ways of controlling *P. minor*. In areas where resistance has not yet developed, isoproturon (IPU) is the most popular herbicide to control *P. minor* [Panwar *et al.*, 1995; Singh & Malik, 1993; Prakash *et al.*, 1986]. IPU is an inexpensive herbicide (around €7.5 ha^{-1}) and, if correctly applied, highly effective against susceptible *P. minor* biotypes. It also controls a wide range of other grassy and broadleaf weeds. IPU can be applied as a pre- or post-emergence herbicide and has long-lasting residual effects. In contrast to water-based spray applications, IPU can be broadcasted manually, mixed with sand or urea fertiliser. IPU as a control agent against *P. minor* was introduced in India in the late 1970s and has been effective against *P. minor* for 15 years. It is therefore not surprising that many farmers, who were confronted with reduced efficacy of IPU against *P. minor* due to resistance development, were reluctant to switch over to alternative, more expensive herbicides.

The alternative herbicides against IPU-resistant *P. minor*, sulfosulfuron, fenoxaprop-P-ethyl and clodinafop-propargyl, are relatively expensive (around €37.50 ha^{-1}) and successful adoption requires access to a spraying kit and mastering of appropriate spraying techniques. As these herbicides have little residual effect, correct timing of application is important. Whereas, under experimental conditions, *P. minor* control after applying these herbicides can be close to 100% [Brar & Singh, 1997; Walia & Brar, 1996; Mirkamali, 1987, 1993], in practice only a few farmers achieve this control rate, because a basic understanding of herbicide application techniques is lacking among many farmers [Bellinder *et al.*, 2002]. The control spectrum of the alternative herbicides is limited to a few grassy weed genera, such as *Avena sp.* and *Phalaris sp.* The possible development of (cross) resistance against one of the new herbicides in the future is a major matter of concern. This is not unlikely, given the fact that *P. minor* biotypes have been reported to be resistant against fenoxaprop-P-ethyl in Israel [Tal *et al.*, 1996] and Mexico [Sayre, 2001]. IPU resistant biotypes in Haryana require higher doses of diclofop-methyl than susceptible biotypes for the same level of control [Malik & Singh, 1993], indicating cross-resistance of IPU-resistant biotypes. Recently, clear signs of cross-resistance of *P. minor* against fenoxaprop-P-ethyl have been reported in Haryana [Yadav *et al.*, 2002a], as well as Punjab [Bhullar *et al.*, 2002, Brar, 2002]. In Brar's study, the fenoxaprop-P-ethyl requirement to kill 50% of the *P. minor* plants more than doubled in a farmer's field when the herbicide was used for two subsequent years. IPU-resistant *P. minor* plants also showed weak signs of cross-resistance against clodinafop-propargyl, but not against sulfosulfuron.

Some farmers, confronted with IPU-resistance, use metoxuron against *P. minor*, because it is inexpensive as IPU and effective in controlling IPU-resistant *P. minor* [Joshi & Singh, 1981; Walia & Gill, 1985a]. However, metoxuron is phyto-toxic to wheat at a dose just slightly above the dose required to control *P. minor*, and consequently, metoxuron application often causes crop damage. Besides, metoxuron is a urea-based herbicide like IPU and its control mechanism resembles that of IPU and therefore, *P. minor* may quickly develop cross-resistance against metoxuron. For an extensive review on herbicides used for the control of *P. minor* under various agro-climatic conditions, see Singh *et al.* [1999a].

In 2000, scientist from Pantnagar Agricultural University, Uttar Pradesh, India, sponsored by the Monsanto company, created transgenic versions of three locally grown wheat varieties [Gopalakrishnan *et al.*, 2000]. The genetically modified varieties were resistant against the non-selective herbicide gluphosinate ammonium, which controls most weeds including *P. minor*. Though the genetically modified wheat varieties have not been tested in the field yet, their use is expected to improve *P. minor* control by allowing the use of non-selective herbicides. In the long term however, *P. minor* may also develop resistance against gluphosinate ammonium. Another potential disadvantage is that genetically modified sowing seeds are relatively expensive, and such technologies may therefore only be accessible for wealthier farmers.

1.3.2 Wheat varieties

As mentioned before, an important driving variable behind the *P. minor* epidemic is the use of short-strawed wheat varieties with poor weed suppressing abilities. Paul & Gill [1979] found that *P. minor* dry matter accumulation is three to four times higher in competition with dwarf wheat varieties, as compared with the traditional tall-strawed varieties. The difference in dry matter accumulation resulted in a *P. minor* seed production of 1550 seeds per plant when competing with dwarf wheat varieties, compared with 250 seeds when competing with traditional varieties. Lemerle *et al.* [1996] compared the abilities of different world genotypes of wheat to suppress *Lolium rigidum* and ranked the Indian genotypes, along with varieties from the Middle East and the Mediterranean, as the least competitive. Most Haryana farmers select wheat varieties on the basis of yield characteristics and are barely aware of the competitive abilities of the cultivars. Consequently, the most popular wheat variety in

Haryana, PBW343, is a highly productive variety, but poorly competitive against weeds [Brar *et al.*, 1997]. Until recently, it is also true that Indian plant breeders have paid little attention to the competitiveness of the varieties.

Among the modern dwarf-sized varieties, there is considerable variation in weed suppressing abilities. In general, morphological plant properties, such as plant height, early biomass accumulation, tiller number, leaf display and shading abilities, determine the competitiveness of a wheat variety [Lemerle *et al.*, 1996; Richard & Davies, 1991]. Brar *et al.* [1997] reported that, under Indian conditions, high numbers of mature tillers at harvest is associated with good competitive abilities, while final plant height is a relatively unimportant trait. These finding are diametrically opposed to the results published by Balyan *et al.* [1991], who found that height and early dry matter accumulation are better predictors of the competitive ability of Indian wheat varieties than number of tillers.

1.3.3 Rotational crops

Rotating wheat with other winter crops breaks the lifecycle of *P. minor* and assists in reducing the weed's population size. Farmers estimate a 90% reduction in seedling density after a season with an alternative winter crop. Alternative winter crops prevent *P. minor* seed shed and sometimes allow the use of herbicides against *P. minor* which are non-selective against wheat. Cultivation of berseem (*Trifolium alexandrium*), which is raised by most farmers as cattle fodder on small plots of land, is highly effective in exhausting the seed bank of *P. minor*. Regular irrigations during the berseem cultivation, stimulate *P. minor* seeds to germinate, while monthly harvests of berseem prevent *P. minor* to set seed. Sugarcane is a common crop in the northwestern areas of Haryana, which have been severely infested by IPU-resistant *P. minor* biotypes. Sugarcane has the potential to strongly reduce *P. minor* population size, due to its smothering effect on *P. minor* plants in its later growth stages and by allowing the use of alternative herbicide, such as atrazine and simazine, to which IPU-resistant *P. minor* is sensitive. Generally, pulse crops, which are commonly raised in the drier sandy areas of southern Haryana, as well as vegetables, are poor competitors with *P. minor*. However, by allowing the use of alternative herbicides, pulse crops or vegetables may also contribute to *P. minor* control [Singh *et al.*, 1999a]. Barley suppresses *P. minor* considerably better than wheat [Afentouli & Eleftherohorinos, 1996], due to barley's vigorous early growth, but it is rarely cultivated in Haryana because of a lack of demand. In conclusion, rotating wheat with other winter crops can be very beneficial for *P. minor* control, but, as mentioned before in Section 1.1.1, the possibilities for diversification of the cropping system in Haryana are rather limited.

1.3.4 Cultural methods

The benefit of cultural methods, such as increased seed rate, bi-directional sowing and narrow row spacing, to control *P. minor* has been studied in experimental trials on the Indo-Gangetic plains. Although results of these trials were sometimes promising, few farmers in Haryana bring any of these methods into practice. An increase in seed rate from 100 (recommended rate) to 150kg ha^{-1} reduced weed dry weight and increased wheat grain yield [Panwar *et al.*, 1989 and 1995]. In addition, these studies reported that cross sowing was beneficial for weed control and grain yield as compared with normal sowing, which is in line with the results of Prakash *et al.* [1986]. Brar & Singh [1997] reported that narrowing row spacing from 22.5 to 15cm reduced *P. minor* dry matter accumulation by 36%, while bi-directional sowing gave a 30% reduction in *P. minor* biomass, resulting in, respectively, 10 and 15% higher wheat yields. Also Dhiman *et al.* [1985] reported that narrowing row space from 22.5 to 15cm reduced *P. minor* populations, while increasing wheat seed rate from 100 to 150kg ha^{-1} had no effect.

Sowing time is an important factor determining the outcome of the crop weed competition. Advancing sowing time from mid November to late October reduces *P. minor* pressure because of the weed's germination requirements [Bhan & Choudary, 1976; Paul & Gill, 1979]. While the average day temperature of 25^0C at the end October is too high for *P. minor* germination, day temperatures of around 15^0C at the end of November and the beginning of December are optimal [Paul & Gill, 1979]. Also wheat yield benefits from early sowing. Each week delay of sowing beyond the end of October results in a decrease in expected yield of 0.35 to 0.60t ha^{-1} [Bhan & Shushilkumar, 1998]. Despite the benefits of early sowing for *P. minor* control and wheat yield, only few farmers realise early sowing. The intensive cropping system, which may include two rice cultivations or a long-duration Basmati-rice cultivation, retards wheat sowing. In addition, delayed availability of soil cultivation and sowing machinery often retards wheat sowing.

Recently, a number of new ploughing and sowing techniques, which may assist with *P. minor* control, have been introduced in Haryana. Raised-bed planting in wheat is a promising sowing technique, which is presently in the demonstration phase. The technique originates from Mexico, where farmers use it on about 0.5m ha of irrigated land. With this system, two or three rows of wheat are planted on beds of about 70cm width. Raised-bed planting has the advantage that it allows mechanical or manual inter-bed weed control. Weeds growing on top of the beds are also easily accessible for manual weeding, whereas with traditional flat-land sowing, manual weeding often causes crop damage. In addition, space in between the beds facilitates irrigation and consequently, raised-bed planting increases water use efficiency by 30-40%, as compared with traditional planting on flat land [Hobbs *et al.*, 2000]. The technique of raised-bed planting is presently being adapted to rice. Costs of making the beds after every rice harvest are a constraint for wide-scale adoption of raised-bed planting. These costs may be reduced by creating permanent beds on which each successive crop is planted on the previous residue [Hobbs, 2002]. Bed-planters are manufactured locally in Amaritsar, Punjab, and cost around €425. Another new soil cultivation technique in Haryana is mouldboard ploughing, which is presently tested at HAU experimental farm. Mouldboard ploughing is expected to move *P. minor* seeds to deeper soil layers, where they fail to emerge and are likely to die of exhaustion [Malik, 2002, pers. comm.]. Another soil cultivation technique, zero tillage, has quickly gained popularity among farmers since its introduction in 1996. As this technique may have far-reaching consequences for the wheat cultivation and the rice-wheat system in general, it is discussed below in a separate section.

Manual weeding is mostly practiced by small farmers and is more effective on sandy than clayish soils [Singh *et al.*, 1985]. Manual weeding as a mean to control *P. minor* is labour intensive and is therefore not feasible for farmers with large landholdings. To prevent yield loss, *P. minor* should be removed in January or early February. Many farmers and landless people collect *P. minor* for cattle fodder later in the season. This practise is usually not effective in reducing crop-weed competition, but it reduces the number of weed plants setting seed at the end of the season, and may diminish weed emergence in the subsequent year. Raised-bed planting facilitates manual weed control, and more frequent use of raised-bed planting in the future may coincide with increased popularity of manual weeding.

1.3.5 Zero tillage

Zero tillage is a relatively new soil cultivation technique for the Indo-Gangetic plains, and may have important implications for weed control. Under zero tillage, wheat seeds are directly drilled into the stubbles of the previous crop (usually rice in Haryana), without any preceding soil cultivations. Zero tillage systems and concepts have evolved rapidly since the early 1960s and are now applied worldwide. The reason behind this increasing popularity of zero tillage is that it has some clear advantages above conventional tillage methods, as summarised by Phillips [1984]. Wind and water erosion of soil is strongly reduced by zero tillage agriculture. Since much of the world's soils devoted to crop production have limitations associated with erosion, this advantage has played an important role in the adoption of zero tillage. Furthermore, zero tillage has the advantage that diesel fuel requirements for land preparation are about 60-75% less, as compared with conventional tillage techniques. Zero tillage offers the opportunity to plant under higher soil moisture conditions and therefore, allows more flexibility in planting time and a more intensive cropping system. Zero tillage reduces labour requirements for soil cultivation and crop sowing by roughly 50%. Zero tillage improves the soil's capacity to retain water and reduces evaporation. Increased water infiltration and reduced run-off under zero tillage further improves the soil water balance. Soil temperatures in the upper layer are reduced in the field under zero tillage, which is an advantage in (sub)tropical climates, where soil temperatures may be too high for optimal plant growth and development. However, reduced soil temperatures could be a disadvantage in temperate climates, where zero tillage may aggravate problems with cool soils for warm season crops. Another potential disadvantage of zero tillage is that residues at the surface from the previous crop can retard seedling establishment and early crop growth [Prew *et al.*, 1995; Rasmussen *et al.*, 1997]. In addition, zero tillage may cause an increase in biological activity of the soil and overall insect diversity, including an increased incidence of diseases and pest insects [Gebhardt *et al.*, 1985].

The effect of reduced tillage on weed communities is complex. The development of herbicides for suitable weed control has been a prerequisite for the acceptance of zero tillage for crop production in many parts of the world [Witt, 1984], stressing the importance of appropriate weed control for the success of zero tillage systems. Numerous studies have been conducted in temperate regions on the effects of zero tillage on weed communities, often with contrasting results. The effect of zero tillage on the abundance of grassy and broadleaf weeds differs from species to species [Barbarpour & Oliver, 1998; Vencill & Banks, 1994; Buhler & Mester, 1991; Froud-Williams *et al.*, 1981 and 1983] and depends on factors such as cropping pattern, herbicide use, environmental conditions and input levels [Kegode *et al.*, 1999].

Tillage regime affects the relative distribution of seeds throughout the soil profile [Clements *et al.*, 1996]. Zero tillage often results in an accumulation of seeds in the upper 2cm of the soil, which is for the majority of weed species favourable for germination [Yenish *et al.*, 1996, 1992; Buhler & Mester, 1991]. However, seed dormancy can be altered by mechanical or light stimulation during ploughing [Botto *et al.*, 1998] and for many species, soil disturbance enhances seed germination [Roberts & Feast, 1973; Froud-Williams *et al*, 1984]. Tillage regime affects conditions for seed germination, as well as decomposition and predation pressure through changes in soil microenvironment. Tillage regime may change the soil porosity, bulk density, soil surface conditions, pH and microbial activity [Gebhardt *et al*, 1985; Lal *et al.*, 1994]. In addition, stubbles that remain on the soil surface after zero tillage may change germination conditions for weeds by diminishing temperature fluctuations and light intensity at the soil surface [Froud-Williams *et al.*, 1981]. Along with germination rate, seed longevity and depletion rate of the soil seed bank are affected by tillage regime, and the nature of the effect varies from study to study. An accumulation of seeds in the upper soil layers, as often observed in zero tillage, may result in higher germination and decomposition rates. If the seedbank is not replenished with newly shed seeds, depletion of the seed bank may be accelerated by the application of zero tillage systems.

In Haryana, initial acceptance rate of zero tillage in wheat was slow, because it was hindered by firm convictions in favour of conventional tillage methods. For a long time, farmers considered extensive soil operations before wheat sowing necessary to clear the surface from debris from previous crops and to avoid the negative effects of puddling on soil structure. Puddling is one of the key soil management practices in rice and drastically changes soil physical and chemical properties. Puddling breaks capillary pores, reduces void ratios, destroys soil aggregates, disperses fine clay particles and lowers soil strengths in the puddled layer. This helps to control weeds, improves water and nutrient availability and facilitates rice transplanting. With repeated puddling over years, clay particles settle into a dense zone at the base of the tilled layer, which supports a perched water table and restricts water loss by percolation. While puddling is beneficial for rice cultivation, the destruction of soil aggregates, compaction of the soil and the formation of dry surface crusts after drying has a negative impact on wheat establishment and early growth [Timsina & Connor, 2001].

Therefore, extensive tillage operations to break the hard pan before wheat sowing have been considered an indispensable part of the wheat cultivation for long time.

However, experience with zero tillage in Haryana has shown that zero tillage overcomes the problem associated with poor soil structures by allowing rapid establishment of wheat after rice before crusts and cracks appear [Hobbs *et al.*, 1997]. Negative effect of rice stubbles on wheat emergence and early crop growth have not been observed in fields under zero tillage, if the stubbles are attached to the roots, which is the case after manual harvesting of rice. Under Haryana conditions, high temperatures and humid soil conditions enhance quick degradation of crop debris during the early stages of wheat growth. Loose stubbles, which are left behind on the field after combine harvesting of rice, may retard early wheat growth in fields under zero tillage. Most farmers practicing zero tillage, who are faced with the problem of disposing loose straw on their fields, burn the straw, which has several negative side effects [Section 1.3.6]. Other farmers remove the stubbles from the field or conduct one planking operation to disperse the stubbles before sowing wheat with a zero-till drill. The term 'minimum tillage' would be more appropriate for the latter system. Handling of loose rice straw is a constraint for application of zero-tillage after rice harvesting with a combiner.

As noted previously, results of studies conducted outside India on the effects of zero tillage on weed communities are highly variable. Zero tillage in wheat in Haryana is not a complete no-tillage system, because the soil is still cultivated before the rice cropping. Therefore, only limited predictions can be made of how zero tillage will affect weed densities, based on currently available literature. Problems with pre-sowing weeds are limited in the rice-wheat system. The agro-ecological conditions of the rice and wheat cultivation differ so greatly that only few weeds are present at the time of wheat sowing. Therefore, the majority of the Haryana farmers practicing zero tillage do not require any pre-emergence herbicides for weed control. Zero tillage in Haryana is likely to affect *P. minor* germination conditions, relative seed distribution through the soil profile, seed longevity and dormancy. Four-year experience with zero tillage has shown that adoption of zero tillage in combination with the adoption of foliar applied herbicides results in a reduction of *P. minor* populations, compared with conventional tillage [Singh *et al.*, 2002b]. The observed reduction in *P. minor* populations could be related to the advanced sowing time of fields under zero tillage, which reduces *P. minor* emergence [Section 1.3.4], as well as to differences in soil physical and chemical structure and seed dormancy status. Broad-leaf weed species, especially *Rumex maritimus* and *Chenopodium album*, may benefit from reduced soil disturbance in fields under zero-tillage, but this has not been confirmed by field observations.

Reduced tillage in wheat in Haryana leads to an increase in overall insect and spider diversity and a potential increase in incidence of the pest insects, such as the pink rice stem borer (*Sesamia inferens*) and the yellow rice stem borer (*Scirpophaga incertulas*) [Jaipal *et al.*, 2002]. If rice stubbles are not incorporated into the soil and remain on the surface, as in zero tillage systems, survival chances of hibernating larvae of these pest insects may be higher, causing problems in subsequent rice cultivations. A study on the variation in soil nematode populations between fields under conventional tillage and zero tillage in Haryana did not reveal any significant differences [Dabur *et al.*, 2002]. Zero tillage was introduced in Haryana in 1996 and it may take ten years from the moment a new tillage system is introduced until the agro-ecosystem reaches a new equilibrium [Gebhardt *et al.*, 1985]. Therefore, little can be said about the long-term effects of zero tillage on the qgro-ecology in northern India based on current experience.

While anticipated problems with wheat establishment, stubble management and weed control have not occurred in fields under zero tillage in Haryana, advantages of adopting zero tillage are considerable. The main advantage of zero tillage is reduced cultivation costs, because of lower diesel and labour requirements during sowing and reduced tractor maintenance costs. Farmers save between €45 and €50 ha^{-1} by adopting zero tillage [Malik *et al.*, 2002]. Early sowing and good crop establishment results in equally or better wheat yields in fields under zero tillage compared with conventional tillage [Yadav *et al.*, 2002b], as well as reduced *P. minor* populations. During first irrigation, it takes less time for water to flow across the field in zero-tilled fields, resulting in water savings as well as reducing the tendency for farmers to apply too much irrigation water, which often leads to waterlogging and yellowing of the crop [Hobbs, 2002]. These considerable advantages have resulted in a rapid adoption of zero tillage practices in Haryana. In 2002, the number of zero-till drills in Haryana was estimated to be around 2050, while the area under zero tillage had increased from 36ha in 1997-98 to 90 000ha in the 2001-02 growing season [Punia *et al.*, 2002]. The main drawbacks for adoption of zero tillage are presently the investments necessary to purchase or hire a zero-till drill and a tractor with sufficient power, which is especially a drawback for small farmers who still cultivate their land with animal power. Zero-till drills are manufactured locally in Ludhiana (Punjab) and Pantnagar (Uttar Pradesh), and cost around €400. Demand for zero-till drills presently exceeds the local production capacity.

While zero tillage in wheat is mostly practiced in rice-wheat rotations, the technique has been successfully applied in cotton-wheat [Sirohi *et al.*, 2002] and maize-wheat rotations [Singh *et al.*, 2002a], in combination with pre-emergence herbicides. On the Indo-Gangetic plains, adoption of zero tillage is mostly confined to Haryana, Punjab and western Uttar Pradesh, as farms in this area are more mechanised than farms in the eastern parts of the Indo-Gangetic plains. In addition, the agricultural universities in the western Indo-Gangetic plains, HAU, Punjab Agricultural University and Pantnagar Agricultural University (western Uttar Pradesh), have been actively involved in the promotion of zero tillage. First trials with zero tillage in wheat have been conducted in eastern Uttar Pradesh [Yadav *et al.*, 2002c], Madhya Pradesh [Yaduraju & Mishra, 2002], as well as Bihar [Prasad *et al.*, 2002], but for wide-scale adoption of zero tillage in these areas the technique needs to be further adapted to local environmental and socio-economic conditions.

The benefit of zero tillage in reducing *P. minor* populations is significant, but moderate. However, anticipated changes in the present practices of soil puddling and transplanting of rice towards reduced soil cultivation and direct seeding of rice may cause a major shift in weed flora in the rice as well as the wheat cultivation. The main drivers for changes to current cultivation methods are the destructive effects puddling on the soil physical properties and the reducing availability of labour to nurse and transplant rice seedlings. Presently, in Haryana, rice transplanting is almost entirely conducted by contract labour from the eastern state Bihar, but demographic trends indicate that this type of labour will become scarce in the future and labour costs will increase [Singh *et al.*, 2002c]. Weed control and suitable seeding equipment is still a constraint for wide-scale adoption direct-seeded rice, but results from research trials are promising and direct seeding in rice may be the next major tillage innovation on the Indo-Gangetic plains.

1.3.6 Crop residue management

Crop residue management is an important aspect of zero tillage systems, because straw residues may retard early crop growth and affect germination conditions for crops and weeds. Stubble burning or removal can prevent retardation of early crop growth [Prew *et al.*, 1995; Rasmussen *et al.*, 1997], but these practices may affect weed pressure by changing germination conditions and efficacy of applied herbicides. In Haryana, negative effects of rice residues on wheat growth in fields under zero tillage are limited to fields covered with loose rice stubbles after combine harvesting of rice. Nevertheless, many Haryana farmers, irrespective of the applied tillage system, burn rice stubbles.

Generally, burning improves pest and weed control by destroying weeds, diseases and pest insects and it changes soil chemical and physical properties. These benefits often result in higher crop yields in straw-burned plots [Chilcote *et al.*, 1980]. In addition, burning releases nitrogen bound by straw residues. Unbound nitrogen is directly available for plant uptake, benefiting plant growth, but is also susceptible to leaching. Therefore, burning may enhance the loss of nitrogen and soil organic matter, as compared with stubble incorporation [Mason, 1992]. Other negative effects of burning include air pollution and production of the greenhouse gas carbon dioxide. For these reasons alone, stubble burning is not allowed in many developed countries.

Moss [1980] observed that high temperatures during straw burning are effective in destroying many weed seeds on the surface. The higher quantity of straw, the greater control of the weeds. After straw burning, the soil surface was a better environment for germination of surviving seeds than germination under straw stubbles and seeds receiving a mild heat shock were stimulated to germinate. This is in line with findings by Wilson & Cussans [1975], who reported that wheat stubble burning reduced the number of viable seeds of grass weed *Avena fatua* recovered from the surface by 32% directly after burning, but stimulated surviving seeds to germinate. This resulted in higher weed seedling densities in burned plots. Absorptive capacity of ash remaining on the surface after burning has been related to reduced efficacy of plant protecting chemicals. Moss [1985] studied the effect of straw burning and cultivation regime on populations of black grass (*Alopecurus myosuroides*) and its control by IPU and chlortoluron in the UK and reported reduced IPU-efficacy after straw burning followed by direct drilling of wheat, which was attributed to the adsorptive capacity of burned straw-residues on the soil surface.

Under Haryana conditions, rice-wheat farmers are faced with the disposal of the stubbles of both rice and wheat and stubble management of both crops may affect *P. minor* population dynamics. The effects of straw burning on grassy weeds in the rice-wheat system may be different from those found by Moss [1980] and Wilson & Cussans [1975], since residues of two crops are involved. Burning of wheat straw may be an efficient way to kill recently shed *P. minor* seeds, which, at the time of burning, have not been incorporated into the soil yet. Freshly shed seeds are in primary dormancy during wheat stubble burning and it is unknown whether burning has any effect on the dormancy duration or status of the surviving seeds. The effect of wheat straw burning on herbicide efficiency in wheat is likely to be negligible in a dual cropping system. Wheat straw burning is rarely practised, because wheat straw is a valuable product, used as cattle fodder, for building purposes, or as fuel. Therefore, farmers prefer removal of wheat straw to burning or incorporating it into the soil.

Rice straw on the contrary, has little commercial value and is often burned for disposal, which may affect *P. minor* viability, germination rate and herbicide efficacy in wheat. By the time rice straw is burned, most *P. minor* seeds have been incorporated into the soil by tillage and puddling operations associated with the rice cultivation. As strong heat during burning is confined to the soil surface, the effect of rice straw burning on overall *P. minor* seed viability may be small. A mild heat shock, as experienced during burning by seeds under the soil surface, as well as an increased availability of nutrients after burning, may enhance *P. minor* germination rate.

Singh *et al.* [1999b] reported that rice straw burning under herbicide-free conditions resulted in an increased weed population and weed biomass accumulation and, consequently, in reduced wheat yields. Furthermore, they found a reduced efficacy of IPU after rice straw burning, possibly as a result of the adsorptive capacity of ash on the soil surface. These results were in line with findings by Kumar *et al.* [2002], who also measured the IPU-adsorption by the soil and found that straw-burned plots had adsorbed more IPU than plots where straw was incorporated or removed. Brar *et al.* [1995] however, did not find any effect at all of rice or wheat straw burning, rice straw removal or rice straw incorporation on *P. minor* populations, herbicide efficacy or wheat yield. Therefore, they recommended the incorporation of wheat and rice straw residues into the soil to avoid air pollution and loss of nutrients and to enhance soil organic matter contents. Both Singh *et al.* [2001] and Sarkar [1997] report a stimulatory effect of rice and wheat residue incorporation, compared with straw removal, on yield of both rice and wheat. They did not include the effect of burning in their experiments. The question of whether rice residues should be burned, incorporated or removed is complicated by the fact that only few farmers uniformly distribute straw over the field prior to burning. Most farmers burn rice straw in piles, resulting in strong heating up of the soil and accumulation of ash on relatively small plots of land. This factor has not been included in any of the above-described studies.

1.4 Modelling weed population dynamics

1.4.1 Why modelling?

It is often questioned whether the vast amount of money and effort currently invested in modelling weed population dynamics are justified. Although it is true that the contribution of weed population models to the development of weed management systems has been rather modest so far, population models serve as a valuable research tool to summarise and integrate existing knowledge on lifecycle processes. In particular, weed population models help to identify information gaps, set research priorities and suggest control strategies. In addition, several key questions in weed control cannot be answered using conventional field trials, because of the constraints of costs, time or complexity [Doyle, 1997].

Up to the 1990s, most weed population models focussed on the effects of weed density and duration of competition on crop losses [Cousens, 1985a and 1985b], which has provided little understanding of the mechanisms by which plants interact with each other [Norris, 1992]. From the 1990s on however, eco-physiological models for interplant competition for light, water and nutrient resources have provided more mechanistic understanding of how plant species compete [Kropff & Laar, 1993]. In addition, more recent lifecycle models have included other aspects of the weed's lifecycle than interference and competition, such as reproduction [Medd & Ridings, 1990], seed bank dynamics [Vleeshouwer & Bouwmeester, 1993] or spatial dynamics of weed populations [Moody & Mack, 1988]. The current state of the art in modelling lifecycle processes has been described by several authors [Fernandez-Quintanilla, 1988; Cousens & Mortimer, 1995; Colbach & Debaeke, 1998; Doyle, 1991, 1997; Doyle *et al.*, 2001] and this section does not aim to provide another review of the use of population models in weed science. After a summary of the biology behind two important aspects of weed population models, seedbank dynamics and inter-plant competition and mortality, three examples will be provided of how weed population models have contributed to the development of weed management programmes in the past.

1.4.2 Biology behind plant population models

1.4.2.1 Seedbank dynamics

Generally, understanding of weed seedbank dynamics is still rather poor, in spite of a vast amount of work on seed dormancy and germination. This poor understanding may be the result from limited availability of data from field studies, especially from data sets where all relevant environmental variables were monitored [Kropff *et al.*, 1996]. The complex processes in the soil in relation to soil seedbank dynamics, such as predation and decomposition, are difficult to monitor and have therefore often been ignored. Norris [1992] argued that the most significant control of weeds may be endemic, and that it occurs at the level of seed predation on and in the soil, otherwise we would be 'up to our knees in weed seeds'. Our poor understanding of seedbank dynamics is reflected by most lifecycle models, devoting relatively little attention to seedbank dynamics. This is a major weakness of many models, because soil processes affecting seedbank dynamics contribute much to the regulation of the population size.

Seedbank dynamics are regulated through the inflow of newly produced seeds and the losses due to mortality and emergence. Forcella *et al.* [1996] acknowledged five types of ecological information required to manage seedbanks:

(1) *Distribution of seeds within the seedbank.* Tillage regime is a major factor influencing both horizontal and vertical distribution of seeds within the seedbank. For *P. minor*, the use of zero or conventional tillage may have a major impact on seed distribution. Cropping pattern is another important factor affecting the distribution of seeds. For instance, the effect of ploughing and puddling operations associated with the summer rice crop on weed seed distribution is very different from the effect of ploughing associated with alternative summer crops, such as cotton or pearl millet.

(2) *Fate of weed seeds at various depths.* Decay of seeds is generally exponential over time [Robert & Feast, 1973; Froud-Williams, 1983], and proceeds typically quicker for annual grasses than for annual and biennial broadleaf weeds [Burnside *et al.*, 1996]. Annual grass weeds, such as *Bromus sterilis* and *Avena fatua*, were found to have a half-life time in the soil of less than one year. On the other hand, many weed species still have a small residue of seeds in a viable state after many years of burial [Lewis, 1973], which shows that long-lasting efforts are necessary to eradicate a weed species in a field.

Decay of seeds is influenced by soil cultivation regime. Robert and Feast [1973] compared the rate of loss of viable seeds in cultivated and undisturbed soils and found that the time until half the seeds lost their viability was 2.2 years in cultivated soils and 5.8 years in undisturbed soils. It is assumed that seeds in disturbed soils are more likely to germinate and suffer more from predation and decomposition. Seed depth also affects seed longevity. Seeds in the upper 1-2cm of the soil are lost due to germination, predation, decomposition, quicker than seeds buried at 10cm depth [Forcella *et al.*, 1996]. A concentration of seeds in the upper layer, compared with an equal distribution of seeds throughout the soil profile, may result in higher germination and emergence rate and consequently, in an increased seed return at the end of the growing season. A concentration of seeds in the upper layer may therefore enhance population size, despite increased seed mortality.

(3) *Emergence percentage.* While the density of seedbanks of arable soils may be very large, between 10^3 and 10^5 seeds m^{-2} [Fenner, 1985], only a small proportion of the total seedbank emerges every year. The seedbank may actually be composed for more than 80% of dead seeds [Forcella, 1992]. In addition, a large proportion of the germinating seeds may not emerge at all, because of depth of burial or mechanical hindrance. Emergence rate depends on depth of burial. Whereas the emergence rate in the upper 1cm of the soil may be close to 100% under optimal conditions [Froud-Williams *et al.*, 1984], the emergence rate of the total viable seed bank typically varies between 1 and 12% [Benoit, 1989]. Other factors that determine emergence rate include soil cultivation, which may break or induce dormancy through mechanical and light stimulation [Bliss & Smith, 1985; Milberg, 1997], and environmental conditions.

Weed seedling populations may be predicted by multiplying the emergence rates by seed bank density. However, factors, such as soil management, seed dormancy status and weather conditions, give rise to large year-to-year variation in emergence rate and it is difficult to include these factors in a model predicting emergence rate. Furthermore, it is difficult to correctly assess the soil seedbank, as seedbank estimates may vary with sampling technique, size, number and date [Forcella, 1992].

(4) *Timing of seedling emergence.* Environmental factors, especially soil temperature and moisture, are the most important factors determining timing of seedling emergence [Cousens & Mortimer, 1995]. Time of emergence is affected by depth of burial of the seeds. Seeds in various layers may experience different environmental conditions and may be in a different state of dormancy. After germination, seeds in deeper soil layers require more time to emerge than seeds near the surface. In Haryana, weather conditions during the wheat cultivation are relatively stable and predictable. *P. minor* seeds require high soil moisture levels for emergence, which are only prevalent directly after irrigation. *P. minor* timing of emergence is therefore largely controlled by the farmer's field management decisions.

(5) *Inflow of newly produced seeds.* Seed production, as a function of plant size, seems a rather stable characteristic of many annual weed species, being uninfluenced by environmental variables [Cousens & Mortimer, 1995]. Simple linear relationships can often be used to describe the relationship between plant biomass and seed biomass, as Thompson *et al.* [1991] showed for five agricultural weed species. Site characteristics, such as soil moisture, temperature and competitive pressure, may have a strong effect on plant biomass, and thereby affecting biomass of the individual seeds and number of seeds per plant.

In contrast to seed production, seed losses on the parent plant and on or in the soil are hard to quantify. Seeds on the parent plant may be lost due to predation by birds, insects and grazing animals, or removed by harvesting machinery. Seeds on or in the soil may also be lost due to predation, mostly by ants, beetles and earthworms, and decomposition by pathogens and fire. Losses of seeds on the parent plant and on the soil due to insect predation may be up to 90% [Sheppard *et al.*, 1989] and may show large year-to-year and spatial variation. For *P. minor*, no attempt to quantify seed losses has been undertaken. As *P. minor* and wheat mature almost synchronously, part of the seeds may be removed during wheat harvesting. Some farmers burn wheat stubbles after harvest, which may kill many *P. minor* seeds lying on the surface. *P. minor* is not known to have any major seed predators. The contribution of soil pathogens to *P. minor* seed mortality is unknown.

1.4.2.2 Plant competition and mortality

Two types of plant mortality can be distinguished: mortality due to extrinsic (density-independent) factors and due to intrinsic (density-dependent) factors [Cousens & Mortimer, 1995]. Weather conditions and weed control measures are among the most important causes for extrinsic mortality in agricultural weed communities. Intrinsic mortality is the result of self-thinning processes caused by intra- and interspecific competition. A first response of plants to competition is a reduction in growth. Intrinsic plant mortality only occurs when competition is intense. For *P. minor* in Haryana, the most important mortality factors are herbicide application and subsequently, competitive pressure from wheat. Later in the growing season, manual harvesting of *P. minor* as cattle fodder may cause large mortality as well. Intra-specific competition is only of importance when weed densities are extremely high. In Haryana, environmental conditions during the wheat cultivation vary little over years, and *P. minor* mortality as a direct result of poor weather conditions is probably rare. However, weather conditions may affect herbicide efficacy and plant growth rate, which in its turn changes the outcome of self-thinning processes.

Extrinsic and intrinsic mortality factors interact with each other. For example, herbicide efficacy is usually not 100%. Surviving weeds are often reduced in biomass, which decreases their chances of survival in the crop-weed competition, despite a reduction in intra-specific competition. At the end of the growing season, weed mortality may be 100%, and it is hard to determine to what extent this mortality should be attributed to extrinsic or to intrinsic factors. In a monoculture, mortality early in the growing season results in a retardation of self-thinning later in the season, which may compensate the loss of biomass earlier in the season. The simultaneous interaction between mortality factors makes it difficult to quantify the contribution of each factor to the total mortality, reducing the accurateness of simulation models.

1.4.3 Models that contributed to weed management programmes

1.4.3.1 An eco-physiological model

An example of an eco-physiological model that has contributed to weed control is INTERCOM. It simulates interactions between plant populations competing for light, water and nutrients [Kropff & Laar, 1993]. Effects of environmental factors, such as rainfall, radiation, temperature and soil hydrological characteristics, are included in the model. The model calculates daily photosynthesis rate based on light interception and photosynthesis characteristics of single leaves. Light interception of a single species is determined by the incoming radiation, leaf area index of the various species and the leaf area distribution over height in a mixed canopy. Growth of different plant parts is calculated by partitioning assimilated carbon over various plant organs, after subtraction of growth and maintenance respiration. Competition for water is simulated using a soil water balance, based on rainfall, transpiration and evaporation. Water stress affects plant growth by reducing the transpiration rate.

INTERCOM may improve our mechanistic understanding of inter-plant competition and possible contributions INTERCOM can make to weed management are diverse. For example, INTERCOM has proven to be a useful tool to identify key traits contributing to the competitive ability of crops. The selection of crop genotypes with an improved competitive ability, based on direct selection of genotypes grown in the presence of weeds, is labour intensive. Indirect selection of genotypes, aimed at attributes that are associated with competitive ability, is a quicker and cheaper method. In this procedure, traits contributing to competitive ability of crops need to be identified prior to the selection procedure. INTERCOM was used to quantify the potential contribution of various attributes to the competitive ability of different rice varieties [Bastiaans *et al.*, 1997]. The model 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. A major disadvantage of detailed eco-physiological models, such as INTERCOM, is the vast amount of environmental and plant data required to parametrise the model. Within the framework of the present study, it was impossible to devote the amount of time and resources required to collect the data and parametrise a detailed eco-physiological model such as INTERCOM. Therefore, the simpler approach of weed population models was considered more appropriate for *P. minor*.

1.4.3.2 A weed population model

Many weed lifecycle models have been developed since the early 1980s; Colbach and Debaeke [1998] reviewed 26 of them. One of them is a model of the population dynamics of *Avena sterilis* in a dry land cereal cropping system in Spain, developed by Gonzalez-Andujar & Fernandez-Quintanilla [1991]. The model included two separate periods of seedling emergence and considered the effects of plant density on mortality and reproduction and was applied to various cropping cereal systems. After construction and parametrisation, all input parameters were subjected to a sensitivity analysis. The analysis revealed that two of the most critical factors influencing population levels were the dispersal and mortality of seeds during the summer and the fecundity of the first cohort of seedlings. The study suggested that further research to these processes in particular could improve *A. sterilis* management in dry land cropping systems.

The model became more valuable when an economic sub-model was added to the lifecycle model, calculating annual net returns under various weed management strategies and cropping patterns [Gonzalez-Andujar & Fernandez-Quintanilla, 1993]. The extended model indicated that the strategy resulting in lowest *A. sterilis* population size was not the economically most attractive management option. Even though the prevailing extensive cropping system was successful in suppressing *A. sterilis*, a more intense cropping pattern with higher herbicide use would be more profitable. To what extent the recommendations suggested by these models have actually changed prevailing weed management and cropping pattern is unknown.

Recently, the population model has been used to study the effects of seed dispersal between fields on weed population size and weed management [Gonzalez-Andujar *et al.*, 2001]. *A. sterilis* population dynamics in two fields was modelled, explicitly including seed dispersal during seedrain between the two fields. This study did not result in any direct recommendations for new management practices. However, the model did indicate that dispersal may play a key role in weed population dynamics and showed that the incorporation of spatial effects produced very different simulation results compared to those obtained from previous models without inclusion of spatial variability.

1.4.3.3 Seed spraying

Avena spp. is also a grass weed of winter cereals in Australia. After intensive studies of the population dynamics of *Avena* spp., a population model was designed and coupled to an economic model [Medd & Ridings, 1990; Pandey & Medd, 1990, 1991; Pandey *et al.*, 1991]. Sensitivity analysis indicated that seed rain by uncontrolled *Avena* spp. was the life stage having the largest influence on the weed population size and persistence. Consequently, the use of herbicides for weed seed kill purposes was pursued and have recently been approved to be applied at low doses during weed seed fill [Mortensen *et al.*, 2000]. The use of herbicides for weed seed kill purposes meant a diversification of the available options to control *Avena* spp. with herbicides and may therefore retard the development of herbicide resistance. Bio-economic modelling also revealed that greater profits would be realised if farmers would adopt a long-term investment approach to weed control, resulting in a recommendation to change the way in which farmers evaluate weed control.

1.5 Research objectives

Given the pressure to maintain high wheat yields in the face of production constraints such as *Phalaris minor*, there is a strong need to improve our understanding of the biological and socio-economic context in which *P. minor* can flourish. New technologies to reduce the pressure of resistant and susceptible *P. minor*, such as herbicides with alternative modes of action and zero tillage systems, have been introduced successfully. However, little is known of *P. minor*'s lifecycle in general and specifically how these new technologies affect the weed's lifecycle. Hence, little can be said about long-term effects of changing weed management practices on *P. minor* population dynamics. Besides, up to recently, the new technologies have been adopted mostly by the most innovative and progressive farmers, which make up only a small proportion of the total farmer community. The chances of successful, wide-scale adoption of new technologies depend on part on their suitability for the system into which they are placed. Therefore, it is necessary to characterise the agronomic and socio-economic factors that are related to the continuing pressure of *P. minor*, along with farmers' ability to change these factors.

Sufficient knowledge of *P. minor*'s biology and ecology, as well as knowledge of the current socio-economic position of rice-wheat farmers, are currently missing. Consequently, this study covered two research areas. One part focused at improving our understanding of the *P. minor* lifecycle, especially seedbank dynamics, and how they are influenced by weed control practices and soil cultivation techniques. The other part consisted of a farming system audit that attempted to identify the underlying agronomic and socio-economic factors that contribute to the continuing pressure of *P. minor* and to assess farmers' ability to change present management practices by adopting more sustainable farming technologies. Special attention was devoted to adoption processes of agricultural innovations and how structuring of the farmer community and the socio-psychological characteristics of the individual farmers influence the outcome of the adoption process.

The present study included the following objectives:

(i) to asses *P. minor* population flux, with special attention for seedbank dynamics, seedling emergence and seed production by adult plants;

(ii) to study the effects of new weed control practices, such as zero tillage and herbicides, on *P. minor* population dynamics

(iii) to summarise existing knowledge of *P. minor*'s lifecycle in a dynamic simulation model and to predict long-term effects of weed control practices on *P. minor* population size;

(iv) to characterise the contribution that agronomic and socio-economic factors make to the epidemiology and control of *P. minor;*

(v) to assess the constraints for Haryana farmers to adopt new technologies and examine the effect of structuring of the farmer community on the adoption rate of new farming technologies.

CHAPTER 2: SEEDBANK STUDIES

2.1 Relevance and aims of the seedbank studies

Despite the economic relevance of *Phalaris minor* as a serious constraint for wheat production in northern India, quantitative knowledge on the biology and ecology of *P. minor* is rather limited. Numerous studies have been conducted aimed at the effect of herbicides [Brar & Singh, 1997; Brar *et al.*, 1999], nitrogen applications [Walia & Gill, 1985a] and sowing techniques [Panwar *et al.*, 1989 and 1995] on the density and biomass of mature *P. minor* plants. The relationship between *P. minor* density and crop yield loss has been studied for Indian conditions [Mehra & Gill, 1988; Dhaliwal *et al.*, 1997, Khera *et al.*, 1995]. Various studies have investigated germination requirements of *P. minor* under laboratory conditions [Okereke *et al.*, 1981; Mehra & Gill, 1988; Chhokar & Malik, 1999]. However, little is known about the seedbank dynamics of *P. minor*. No studies as to *P. minor*'s germination and emergence rates, seed longevity under field conditions and how it is affected by tillage regime, stubble management and environmental factors have been reported.

Knowledge on seedbank dynamics is required to develop and optimise alternative *P. minor* control techniques, such as zero tillage, straw burning or crop diversification, that reduce *P. minor* populations through changes in seedbank dynamics. For instance, field experience has indicated that cultivation of berseem (*Trifolium alexandrium*) allows *P. minor* to germinate but prevents *P. minor* seed shed, resulting in a reduction up to 90% in seedling emergence in the following year. *P. minor* seeds stored under laboratory conditions do not show any sign of reduced viability for 4.5 years and fully loose their capacity to germinate only after 8.5 years [Chhokar, 1998]. Seed longevity under field conditions might be much shorter. It is uncertain whether the strong reduction in *P. minor* seedling density after berseem cultivation should be attributed to rapid seed decomposition under field conditions or to other factors, such as quick exhaustion of the seedbank due to germination during the berseem cultivation. Many farmers burn rice stubbles for disposal. The effects of straw burning on *P. minor* seed viability and germinability are unclear. Hence, no sensible recommendation on straw residue management can be made to farmers yet. New ploughing and sowing techniques, such as zero tillage, mouldboard ploughing and raised-bed planting enjoy increasing popularity in Haryana, while little is known about the mechanisms by which these new cultivation techniques affect *P. minor* population size.

To improve our understanding of *P. minor* seedbank dynamics, three series of experiments have been conducted. The experiments described in this chapter aimed to study:

(i) *P. minor* seed longevity as affected by soil conditions and depth of burial;

(ii) the effects of straw residue burning on survival and germinability of seeds buried at various depths in the soil;

(iii) the vertical movement of seeds in rice-wheat and millet-wheat rotations as affected by different cultivation techniques.

Another major field experiment was conducted to study the effects of zero tillage and herbicides on the lifecycle of *P. minor*, including the effects of tillage on the relative distribution of *P. minor* seeds throughout the soil profile and emergence rate. Set-up and results of this experiment are presented in Chapter 3. For general and *P. minor*-specific information on seed longevity, effects of tillage systems on relative distribution of seed and effects of straw burning on weed populations, see Sections 1.2 and 1.3.

2.2 Materials & Methods

2.2.1 Seed longevity studies

Three complementary series of seed longevity studies were undertaken. The studies were carried out at two sites: the experimental farm of HAU, Hisar and Uchani Regional Research Station, Karnal, Haryana. The soil type at Hisar was sandy loam, at Karnal it was clay loam. Methodology of the three seed longevity studies had much in common. All three studies included two *P. minor* biotypes: an IPU-susceptible and a resistant biotype (S&R biotype); both biotypes were collected in Karnal district. *P. minor* seeds were placed in nylon bags of 4 x 8cm with a pore size of 100μm (2g seed bag^{-1}). Along with the seeds, 15g sieved and sterilised soil from HAU experimental farm was added to each bag. Bags with seeds and soil were buried at Hisar and Karnal at various depths. Per treatment, 26 bags were buried. In addition, seed samples from each biotype were stored under laboratory conditions at room temperature. All experiments were replicated twice.

After burial, bags with seeds were exhumed monthly for the time the experiments lasted. For each treatment, one bag of seeds was exhumed. Within three days after exhumation, germination tests at HAU were initiated. Per bag, sixty seeds which were not visibly decomposed were selected. The seeds were placed on moistened filter paper in three Petri dishes (20 seeds dish^{-1}). Seeds were allowed to germinate in an incubator at 15^{0}C, intermittent light conditions (12h d^{-1}), at a relative air humidity of 80%, for 21d. In the incubator, filter paper in the Petri dishes was kept moist. After 21d, the germination percentage was determined. Germinability of seeds stored under laboratory conditions was tested along with the exhumed seeds in a similar manner. Monthly exhumations were continued until none of the exhumed seeds germinated for three subsequent months.

The three experiments differed in time of burial, seed source, depth of burial and location [Table 2.1]. Study 1 was initiated September 11th, 1999 at Hisar and September 13th, 1999 at Karnal and lasted until August 2001. The site at Hisar was not cultivated during the experiment and received no additional irrigation water. At Karnal, a rice-wheat rotation, which had been the prevailing cropping pattern for the preceding ten years, was maintained during the experiment. Two biotypes of *P. minor* seeds were used: an IPU-susceptible biotype from Uchani Regional Research Station, Karnal, and an IPU-resistant biotype from fields near Bainsa village, Karnal district. Both biotypes were collected in April 1999. Seeds were buried at Hisar and Karnal, 30cm below the soil surface. Ploughing and puddling operations in the rice-wheat system do not disturb bags buried below 20cm. At monthly intervals, 12 bags were exhumed (2 locations x 2 seed sources x 3 replications) and seed germinability was assessed. In addition, along with the seed bags, soil was sampled at both locations to determine the soil moisture content. At each site, 6 soil samples of around 250ml were taken, at 30cm depth. Fresh weight of the soil samples was determined (SWET). Soil samples were subsequently oven-dried (70^{0}C) for 48h and soil dry weight was measured (SDRY). Soil moisture content (SMC) was calculated as follows:

$$SMC(\%) = 100 \cdot (1 - \frac{SDRY}{SWET})$$

Study 2 was initiated June 12th, 2000, and lasted until August 2001. Two *P. minor* biotypes were included: an IPU-susceptible biotype collected at Uchani Regional Research Station, Karnal, and a resistant biotypes collected at a field near village Kulvehari, Karnal district. Both biotypes were collected in April 2000. Bags with *P. minor* seeds were buried only at 20cm depth at Karnal using the same field as in Study 1. Study 3 was started June 26th, 2000 and lasted until July 2001. The experiment made use of the same seed biotypes as Study 2. Bags with *P. minor* seeds were buried only at Hisar site in a field at 0, 5, 10, 20 and 30cm. The cropping rotation was fallow in summer and wheat in winter, which differs from the all-year fallow field used at Hisar in Study 1.

Treatment effects were assessed using analysis of variance (ANOVA). The factors site, seed source and depth of burial were included in an un-nested treatment structure and each experiment was analysed independently. Half-life times of seeds in the seed longevity test were estimated by fitting Gompertz (Study 1&2) or exponential curves (Study 3) in non-linear regression tests and calculating the time at which the germination rate was 50% of the maximum observed germination rate. The choice of the type of fitted curve was determined by the suitability of the mathematical equation to describe the observed germinability course.

Table 2.1 Details of the layout of three *P. minor* seed longevity studies.

	Study 1	*Study 2*	*Study 3*
Period	Sept. 1999 - Oct. 2001	June 2000 – Sept. 2001	June 2000 – July 2001
Location	Karnal, Hisar	Karnal	Hisar
Seed source	R&S, 1999	R&S, 2000	R&S, 2000
Depth of burial	30cm	20cm	0, 5, 10, 20 & 30cm

2.2.2 Seed movement study

2.2.2.1 Bead experiment

To study the effect of ploughing on the relative distribution of seeds through the soil profile, small glass beads were used to mimic *P. minor* seeds. Beads were slightly smaller than *P. minor* seeds and 1000 bead weight was 0.43g (about a quarter of that of *P. minor* seeds). The experiment was conducted at two locations: HAU experimental farm, Hisar and Uchani Regional Research Station, Karnal, Haryana. The experiments were initiated early June, 2000, before the preparation of the land for the summer crop. At Hisar, the summer crop was pearl millet (*Pennisetum americanum*). Pearl millet was sown using a zero-till drill and the soil had not been disturbed between wheat harvest and millet sowing. Wheat was used as a winter crop. Three tillage systems were applied to prepare the soil and sow wheat: zero tillage, conventional tillage using local machinery and tillage with a mouldboard plough. At Karnal, the summer crop was rice, which was ploughed and puddled conventionally. As a winter crop, wheat was cultivated. Three ploughing systems were used to prepare the land and sow wheat at Karnal: zero tillage, conventional tillage using local machinery and raised-bed planting.

At both sites, in each ploughing system, three plots of 5x2m were marked. Beads were spread on the surface of the plots before the summer cultivation, with an average density of 3750 beads m^{-2}. To recover the beads, soil samples were taken in January, 2001. Within each plot, except for raised-bed planting, 10 soil samples were taken randomly with a soil auger, which was 8.6cm in diameter, 20cm deep. Soil samples were split into four soil layers: 0-2.5, 2.5-5, 5-10 and 10-20cm. In each plot under raised-bed planting, 10 samples were taken between the beds and 10 samples within the beds. Beads were separated from soil by washing through sieves at HAU, after which the number of beads per layer was assessed.

The number of beads per volume unit of soil was calculated for each layer. These values were used to analyse variations in relative distribution of beads throughout the soil profile between tillage systems. Significance levels and Least Significant Differences from mean (LSD) were calculated using ANOVA with soil layer nested within tillage treatment. The experiments at Hisar and Karnal were treated as two separate experiments. Seed recovery rate was calculated as the ratio of the number of beads recovered in a plot to the number of beads expected in the soil samples if no beads were lost. Given the soil sampler had a radius of 4.3cm, initial bead density was 3750 seeds m^{-2} and 10 samples per plot (plot size: $10m^2$) were taken, expected number of recovered beads per plot, given no beads were lost, was:

$$\pi \cdot (0.043)^2 \cdot 3750 \cdot 10 = 218$$

2.2.2.2 Seed and soil settling experiments

In addition to the above described bead movement studies, an assessment was made of how *P. minor* seeds may settle in water along with soil particles after disturbance due to puddling. To estimate the effect of puddling on the relative vertical distribution of *P. minor* seeds, the terminal velocity of free falling seeds and soil in water, as well as the settling behaviour of seeds in a suspension with soil particles, was assessed.

The terminal velocity of free falling seeds in water was experimentally determined using a 2-liter cylinder, which was 8cm in diameter and 50cm high. The cylinder was filled with water of 30^0C. *P. minor* seeds collected at Uchani Regional Research Station, Karnal district, April 2001, were released just under the water surface. The terminal velocity of the falling seeds was measured by recording the time seeds required to cover the distance from 20 to 50cm from the surface. It was assumed that after a fall of 20cm, frictional drag due to viscous forces were in equilibrium with the gravitational force and seeds had thus reached their terminal velocity. In total, the terminal velocity of 40 seeds was assessed. The experiment was conducted at the Scottish Agricultural College, December 13, 2001.

The terminal velocity of a soil particle of a certain size can be calculated using Stokes' law. This is an equation relating the terminal settling velocity of a smooth, rigid sphere in a viscous fluid of known density and viscosity to the diameter of the sphere when subjected to a known force field.

The equation for Stokes' law is [Gibbs, 1990]:

$$V = (2gr^2) \cdot (d_1 - d_2)/9\eta$$

V terminal velocity (m s^{-1})

g acceleration of gravity (m s^{-2})

r radius of the particle (m)

d_1 density of the particle (kg m^{-3})

d_2 density of the medium (kg m^{-3})

η viscosity of the medium (Pa s)

In a situation where soil particles of various sizes settle in water of a certain temperature, terminal velocity of a soil particle according to Stokes' law, solely depends on the particle's radius, as the other variables in the equation have the following fixed values:

g	9.81 m s^{-2}
d_1 (soil)	2650 kg m^{-3}
d_2 (water of 30^0C)	995 kg m^{-3}
η (water of 30^0C)	0.761 Pa s

Entering these values into Stokes' equation, the following relationship between soil particle size and terminal velocity was obtained:

$$V = \frac{(2g)\cdot(d_1 - d_2)}{9\eta}\cdot r^2 = \frac{2\cdot 9.81\cdot(2650-995)}{9\cdot 0.761}\cdot r^2 = 4741\cdot r^2$$

Another experiment was conducted to assess the settling behaviour of *P. minor* seeds in a suspension with soil particles. A two-litre beaker was filled with 1.5kg of silty clay loam, collected at an experimental field nearby the village of Narnodh, Hisar district, and mixed with 20g of *P. minor* seed collected at Uchani Regional Research Station, Karnal district, in April 2001. Water was added to the beaker with soil and seeds until the soil surface was covered with 2cm of water. Subsequently, the soil with seeds was manually disturbed until all lumps of soil were broken up, aiming to mimic the disturbances caused by puddling operations in the field. Subsequently, seeds and soil were left undisturbed for 16h to allow seeds and soil particles to settle. Then, seeds and soil were oven dried at 60^0C for 72h. After drying, the hardened soil was removed from the beaker and cut into horizontal slices (0-0.5, 0.5-1.0, 1.0-1.5, 1.5-2.0, 2.0-2.5, 2.5-3.0 and 3.0-5.0cm). Seeds were separated from the soil layers by sieving though 1.0mm sieves and subsequently, the number of seeds in each soil layer was counted. The experiment was conducted SAC Auchincruive, UK, April 26-30, 2002.

2.2.3 Straw burning studies

2.2.3.1 Oven experiment

An oven experiment was conducted to study the effect of various time and temperature combinations in an oven on the germination of dry and imbibed *P. minor* seeds. Susceptible and resistant seeds, used in the experiment, were collected in April 2001. The susceptible biotype was collected at a field near Hisar, the resistant biotype originated from a field nearby the village Kulvehari, Karnal, India. Seeds from both sources were either kept air dry or imbibed on moist filter paper for 36h. Seed samples were then placed on pre-heated glass plates in an oven. The temperatures were 50, 75, 100, 150 and 200^0C and the exposure times were 30, 60, 120, 180, 300 and 600s. A control treatment of imbibed and dry seeds, which were not exposed to heat at all, was also included. There were three replications of every temperature/time combination. The experiment was carried out at SAC Auchincruive, UK, December 2001. Seed germinability was determined, using a method similar to the germination tests in the seed longevity studies.

2.2.3.2 Straw burning field experiments

Two straw burning experiments were conducted at the experimental research farm of HAU, Hisar, Haryana. The methodology of both experiments was largely similar. Both experiments included two *P. minor* biotypes: an IPU-susceptible and a resistant biotype. Prior to burning, *P. minor* seeds were placed on sheets of fine metallic mesh of 10x10cm (1.5g seed $sheet^{-1}$). Sheets with seeds were buried in the soil in plots of 2x2m at 0, 1, 2 and 4cm depth. Each plot included two biotypes, giving eight seed samples $plot^{-1}$. Two quantities of straw were used for burning: 2.4kg straw $plot^{-1}$ (equivalent to 6t ha^{-1}, which approaches the amount farmers burn in the field) and 5.8kg straw $plot^{-1}$ (equivalent to 12t ha^{-1}). Straw was uniformly spread out over the plots' surface and subsequently, burned. After burning, the soil was left undisturbed for 1.5h. Seeds were then exhumed and transported to HAU. In the following weeks, seed germinability was tested in the same way as in the seed longevity studies. All treatments were replicated twice.

The first burning experiment was carried out March 7, 2001. Rice straw was used as a burning agent. Seeds were collected in April 2000. The IPU-susceptible biotype originated from Uchani Regional Research Station, Karnal; the resistant biotype was collected at a field near village Kulvehari, Karnal. Germination tests were initiated March 20 and germination percentage was assessed at 5 and 21d after placement in the incubator. The second experiment was conducted June 26, 2001 and made use of wheat straw as a burning agent. Seed sources were similar to those used in the oven experiment. In addition to other measurements, soil temperature was recorded with two heat-resistant thermometers, at each depth where seeds were buried, at intervals of 30s for 7.5 minutes from the start of burning. Germination tests were started July 25, 2000. Germination percentage was assessed only after 21d of placement in the incubator.

Data on seed germination and soil temperature were analysed using ANOVA. Factors straw quantity, seed source and depth of burial were treated as equal in the treatment structure. The two straw burning experiments were analysed as two independent experiments, because the factors straw type, time of burning and seed source may exert a large influence on the germinability of seeds. Germination data from the burning studies were used to build a mathematical model that simulated the effect of patchy burning on seed survival for various horizontal distributions of seeds throughout the soil profile. Development and performance of the model is explained in more detail in Section 2.3.3.2.

Statistical tests in all experiments of this thesis were conducted using the statistical software package Genstat 5, Release 4.1 [Genstat Committee, 1987], unless stated otherwise. In this thesis, standard errors for means (SE) are presented using error bars in graphs and in parentheses in tables.

2.3 Results & Discussion

2.3.1 Seed longevity studies

The results of the seed germination tests are given in Figures 2.1, 2.2 & 2.3 for Study 1, 2 & 3 respectively. Results of ANOVAs are summarised in Table 2.2 & 2.3. Study 2 did not reveal any statistically significant differences between R and S biotypes. Table 2.4 summarises estimated seed half-life times, given as an average of both seed biotypes, and time required until zero germination occurred.

In most treatments, *P. minor* seed longevity was less than one year. It has been noted before that many annual grass weeds tend to have short seed longevity in the field. Froud-Williams [1983] found a decline in *Bromus sterilis* seed viability of 85% in uncultivated soil in less than a year. Half-lifes of seeds of *Avena fatua* have often been reported to be one year or less [Chancellor, 1986; Miller & Nalewaja, 1990]. Data from all three studies clearly showed prolonged seed longevity for seeds stored under laboratory conditions, as compared with field conditions. While under field conditions, seed viability was strongly reduced after 15 months in all treatments, seeds stored under laboratory conditions did not show any sign of reduced viability after that time of storage [Table 2.4]. A clear conclusion from this comparison is that information on *P. minor* seed longevity of seeds stored under laboratory conditions explains little about seed longevity under field conditions.

In general, seed predation, germination and decomposition are the three most important factors determining seed mortality in the soil [Cousens & Mortimer, 1995]. As seeds in the present experiments were protected by fine nylon mesh, predation by insects or earthworms was unlikely to be an important cause for seed mortality. Seed germination on the contrary, was likely to be a major factor determining seed mortality in the present experiments. However, seedlings could not survive in the nylon bags and quickly died and decomposed after germination. Seeds that germinated in the nylon bags and subsequently decomposed were not selected for the germinability tests after exhumation. These tests assessed the viability of those seeds that remained intact during burial and not the viability of the entire seed population. Therefore, under natural field conditions, where seed predation and germination also contribute to the loss of seed viability, seed longevity may be even shorter.

Table 2.2 Effects of seed source and location of burial on germinability and effect of location on soil moisture content in Study 1, F_{pr} calculated by ANOVA.

Month	*Germinability*			*Soil moisture content*
	Seed	*Location*	*Seed x Location*	
Oct. 99	*0.005*	0.240	0.468	
Nov. 99	0.596	*<0.001*	0.767	0.078
Dec. 99	0.174	*0.012*	0.386	<0.001
Jan. 00	0.961	0.213	0.597	<0.001
Feb. 00	0.281	*0.005*	0.742	<0.001
March 00	0.162	*<0.001*	0.793	<0.001
April 00	0.535	*<0.001*	0.656	0.697
May 00	0.955	*0.002*	0.382	0.032
June 00	0.408	*<0.001*	0.582	
July 00	0.488	*<0.001*	0.488	0.002
Aug 00	0.148	*<0.001*	0.148	0.338
Sept. 00	0.462	*<0.001*	0.462	0.114
Oct. 00	0.536	*<0.001*	0.563	
Nov. 00	0.730	*<0.001*	0.730	0.825
Dec. 00	0.617	*<0.001*	0.617	0.001
Jan. 01	0.785	*<0.001*	0.056	
Feb. 01	0.839	*<0.001*	0.128	
March 01	0.760	*<0.001*	*0.004*	
April 01	0.659	*<0.001*	0.320	
May 01	0.549	*0.049*	0.500	

Table 2.3 Effect of seed source and depth of burial on germinability of *P. minor* seeds in Study 3, F_{pr} calculated by ANOVA.

Month	*Seed*	*Depth*	*Seed x Depth*
July 00	*0.002*	*<0.001*	0.801
August 00	0.125	0.530	0.830
Sept. 00	0.588	*<0.001*	*0.013*
Oct. 00	0.404	*<0.001*	0.673
Nov. 00	0.394	*<0.001*	0.350
Dec. 00	0.452	*0.009*	0.101
Jan. 01	0.338	0.732	0.590
Feb. 01	0.479	*0.041*	0.071
March 01	0.134	0.270	0.215
April 01	0.105	0.398	0.163

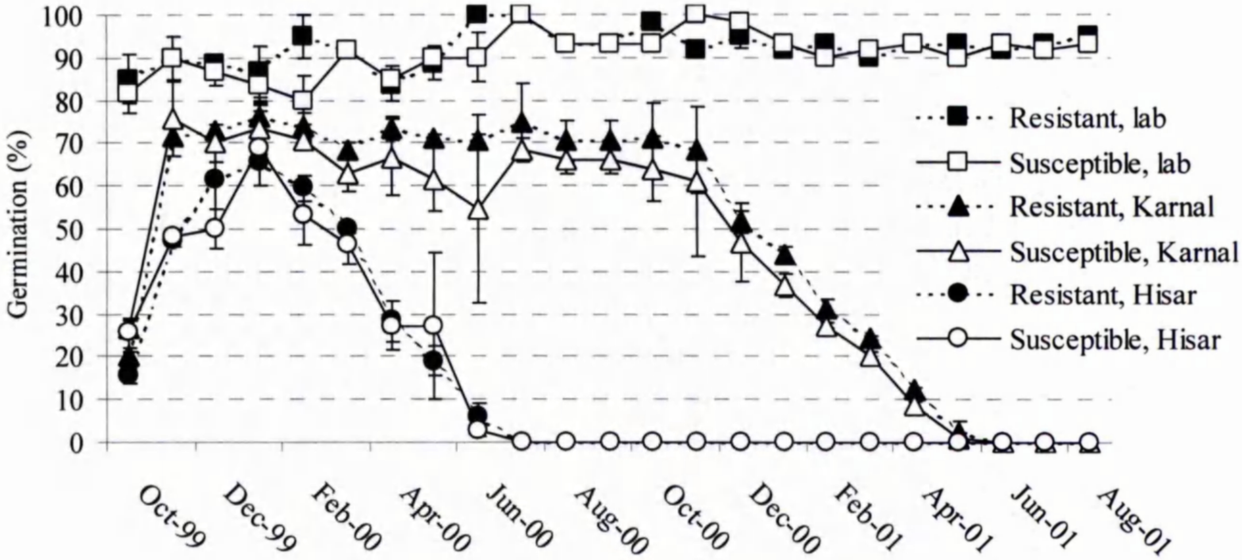


Figure 2.1 Study1: longevity of *P. minor* seeds buried at 30cm at Karnal and Hisar or stored in a laboratory. Average seed longevity was much longer at Karnal than at Hisar.

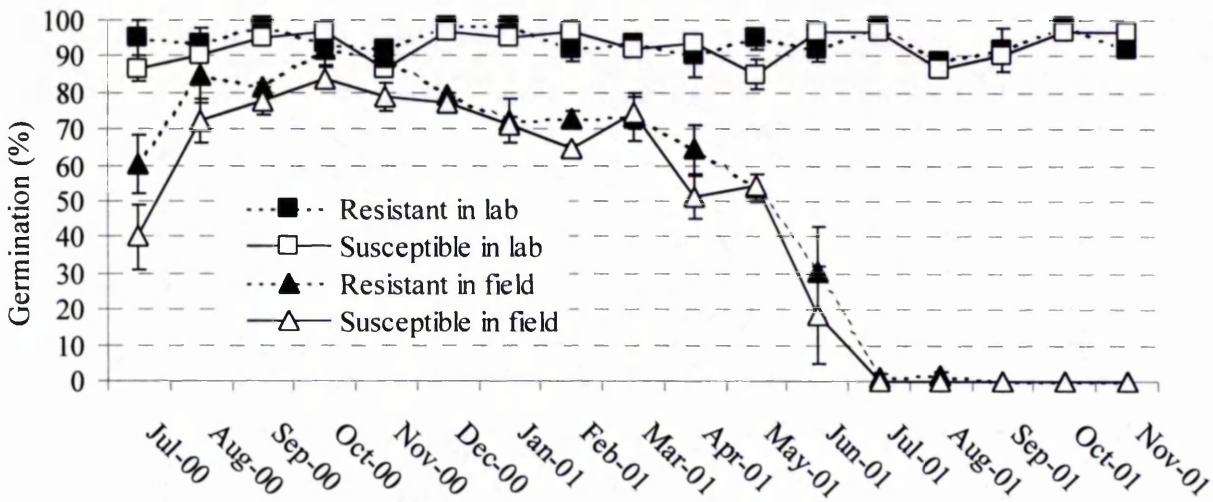


Figure 2.2 Study 2: longevity of *P. minor* seeds buried at 20cm at Karnal or stored in a laboratory.

In the three studies, at first exhumation after one month of burial, germinability was reduced, compared with two to four months of burial. This effect was visible for burial in June 2000 as well as September 1999. In general, low germination rates can be attributed to seed dormancy or to a loss of seed viability. Seeds in dormancy regain their ability to germinate when time and circumstances are favourable, while unviable seeds have lost this capacity. After first exhumation, seed germinability increased. Therefore, it is likely that the observed low germinability at first exhumation was caused by dormancy and not by low seed viability.

Since seeds stored under laboratory conditions did not show a sign of reduced germinability at the first germination test, buried seeds were probably not in primary dormancy. Laboratory-stored seeds experience a large change in environment when being buried in the soil. This change may have induced secondary dormancy in recently buried seeds. After 5-15 months of burial, depending on depth and site of burial, seed germinability started declining irreversibly, indicating a loss of seed viability. After 21 months of burial, none of the exhumed seeds germinated.

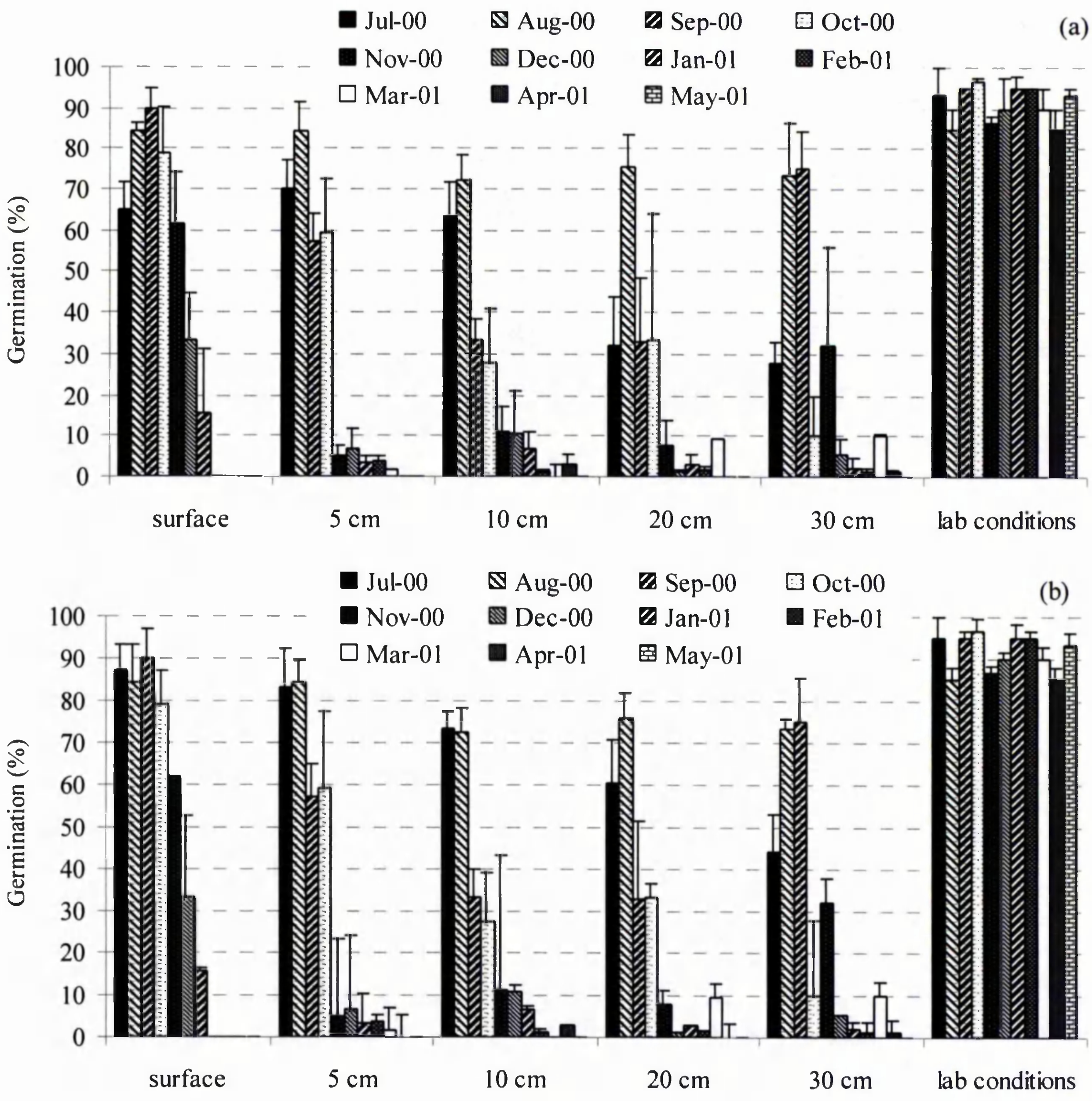


Figure 2.3 Study 3: effect of depth of burial on *P. minor* seed longevity for (a) IPU-susceptible and (b) IPU-resistant biotypes.

Table 2.4 Half-life time after burial and time until no germination occurred in seed longevity studies.

Study	*Site*	*Depth (cm)*	*Half-life (months)*	*No germination (months)*
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[1]	Lab		4 years	8.5 years

[1] (Chhokar, 1998)

Yaduraju *et al.* [1984], Chhokar [1998] and Singh [1998] reported that recently shed *P. minor* seeds exhibit primary dormancy for 3 to 6 months. In this experiment however, there was no sign of primary dormancy after three months of storage under laboratory conditions, suggesting that duration of primary dormancy of *P. minor* seeds may be limited to one or two months.

Resistant seeds germinated slightly better than susceptible seeds at most sampling times. This difference is not significant, except for the first exhumation in study 1 and 3. F probability levels calculated by ANOVA were however so high (0.002 and 0.005 for study 1 and 3 respectively), that this effect cannot be ignored. It indicates a difference in seed physiology between the R and S biotypes, which may be associated with the increased activity of the cytochrome P-450 enzymes of resistant seeds [Singh *et al.*, 1999a]. However, the difference in seed physiology may also be the result of variation in maternal environmental conditions and genetics unrelated to the resistance characteristic. To separate effects of the resistance characteristic on germinability from the maternal environmental and genetic effects not associated with the resistance, several R&S biotypes should be included in an experiment. However, the question of whether there is a difference in seed longevity due to the resistance characteristic is not so relevant for *P. minor* control.

Kremer and Lotz [1988] reported differences in germination and emergence characteristics between triazine R&S populations of *Solanum nigrum*.. The authors managed to explain these differences by variation in germination temperature requirements between resistant and susceptible biotypes. Similarly, Gill *et al.* [1996] reported faster seedling emergence of an herbicide resistant *Lolium rigidum* population compared with a susceptible population. They also acknowledged the need to include several R&S populations in studies like these to account for the considerable variation among weed populations for most biological attributes.

Figure 2.1 shows that location of burial has a strong influence on seed longevity. While in July 2000, seeds buried at Hisar completely lost the capacity to germinate, between 65 and 85% of the seeds buried at Karnal were still able to germinate. Differences in seed longevity between Hisar and Karnal may be related to variations in soil conditions. Karnal soil was heavier, more clayish and poorer aerated than the sandy loam soil at Hisar. Karnal soil was compacted because of the intensive puddling operations associated with the rice cultivation, which destroys soil aggregates and allows fine clay particles to form a compact soil layer. The rice-wheat rotation at Karnal required high amounts of additional irrigation water, while the fallow field at Hisar did not receive any irrigation water at all. Consequently, soil moisture content at 30cm depth was in most months significantly higher at Karnal than at Hisar [Figure 2.4 & Table 2.2]. Extremely high soil water content measured at Karnal in June 2000 was caused by irrigation water applied just before soil sampling. Differences in soil moisture content between the two sites were not significant between August and November 2000. In this period, rice matures and does not require much additional irrigation water. Similarly, during the wheat harvest in April, fields do not receive any additional irrigation water. Soils at Karnal and Hisar may also differ in other respects, such as chemical composition, biological activity, day temperature and temperature fluctuations. There are two possible explanations for the observed variation in seed longevity between the two sites, which do not necessarily exclude each other. Firstly, since both seed biotypes were collected in Karnal district, seed longevity at Hisar may be reduced because of poor adaptation of Karnal biotypes to Hisar soil conditions. Secondly, *P. minor* seeds may be generally better adapted to the anaerobic, heavy soil conditions prevailing at Karnal, as was noticed before by Parasher & Singh [1985].

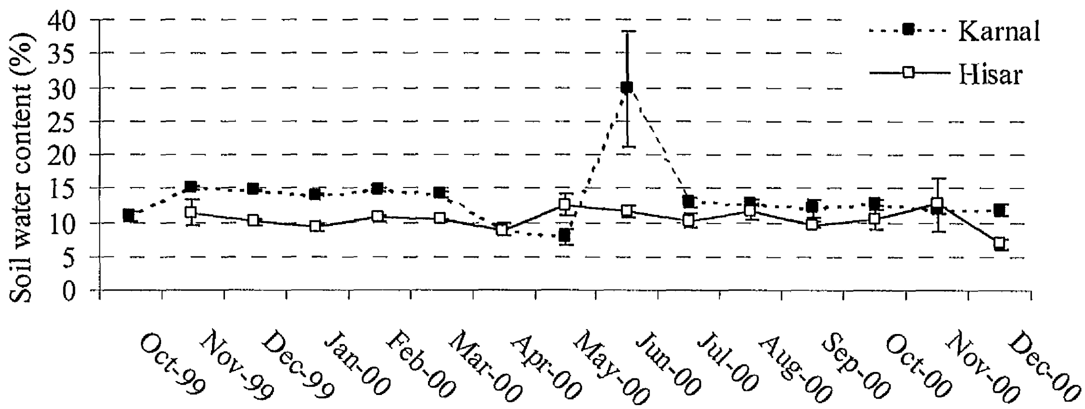


Figure 2.4 Soil water content at Karnal and Hisar in experimental fields where the seed longevity studies (Study 1) were conducted. Soil water content was typically higher at Karnal than at Hisar

Seeds in Study 2, conducted solely at Karnal at 20cm depth, showed similar germination behaviour as Karnal seeds in study 1 for the first nine months. Hereafter, viability of seeds in Study 2 strongly declined, while viability of Karnal seeds in Study 1 remained high. This suggests that deeply buried seeds remain viable for longer than shallowly buried seeds, which was observed also for *Avena fatua* by Miller & Nalewaja [1990]. However, differences in starting time and seed source between Study 1 and 2 prevent us from drawing firm conclusions on the effect of depth of burial on seed longevity.

In Study 3, half-life time of seeds buried at 30cm at Hisar was shorter than the half-life time of seeds buried at 30cm at Hisar in Study 1. This is likely to be related to differences in irrigation pattern. In Study 1 at Hisar, the soil was not irrigated at all, while in Study 3 the field was irrigated in winter to allow the cultivation of wheat. In Study 3, pre-sowing irrigation applied after three months of burial greatly stimulated germination and decomposition of *P. minor* and consequently, decreased half-life time of seeds. Study 3 also stressed the importance of depth of burial for seed survival. While half-life time was roughly equal for seeds buried at various depths, time required until no germination occurred was not. After seven months, germinability of seeds at the surface could not be tested anymore, because no intact seeds could be detected. At this time, all seeds at the surface had germinated or decomposed, while at lower depths seeds maintained their capacity to germinate up to 11 months after burial. These findings were in line with Omami *et al.* [1999], who reported increased germination of *Amaranthus retroflexus* seeds retrieved from upper soil layers, compared with seeds retrieved from lower layers, and Navie *et al.* [1998] drawing similar conclusions on buried and surface-sown seeds of *Parthenium hysterophorus*.

2.3.2 Seed movement studies

2.3.2.1 Bead experiment

Tillage system strongly influenced the relative distribution of beads throughout the soil profile at Hisar (F_{pr} [tillage x layer] <0.001), but not at Karnal (F_{pr} [tillage x layer] 0.142) [Figure 2.5]. At Hisar, millet sown with a zero-till drill, followed by zero tillage wheat, resulted in little horizontal movement of beads; 80% of the beads were still in the upper 2.5cm of the soil and almost no beads migrated below 5cm in the soil. The minimal impact of zero tillage on the movement of beads or seeds resulting in an accumulation of seeds in the upper soil layer in fields under zero tillage have been observed before by Clements *et al.* [1996], Cardina *et al.* [1991] and Cousens & Moss [1990]. Zero tillage millet followed by conventionally tilled wheat resulted in an accumulation of beads between 2.5 and 10cm depth; 88% of the beads were found in this layer. Few beads remained in the upper soil layer and few seeds migrated below 10cm depth. Zero tillage millet followed by wheat, sown after tillage with a mouldboard plough, resulted in a relatively uniform distribution over beads throughout the upper 20cm of the soil. A slight accumulation of beads was observed in soil layer 5-10cm. The LSD value of tillage x layer at 5% at Hisar was 0.21 [Figure 2.5a], indicating that the relative distribution of beads after zero tillage is significantly different from that of conventional tillage and mouldboard ploughing, while observed differences between conventional tillage and mouldboard ploughing were statistically insignificant.

After conventional tillage, few beads were found buried deeper than 10cm from the surface, because local ploughing machinery gives minimal disturbance at this depth. Mouldboard ploughing, on the other hand, disturbs soil layers below 10cm, and consequently, 21% of the beads were found in soil layer 10-20cm. Given that *P. minor* seeds cannot emerge when buried deeper than 10cm [Chhokar *et al.*, 1999; Okereke *et al.*, 1993] and *P. minor* seed longevity under field conditions is rather limited, most of the seeds in this layer are likely to die of exhaustion. In this way, mouldboard ploughing may contribute to *P. minor* control, and therefore may be preferred to conventional tillage techniques.

Table 2.5 Average recovery rate (%) of beads at Hisar and Karnal.

	Hisar	*Karnal*
Conventional tillage	88	18
Zero tillage	91	19
Mouldboard plough	61	
Raised bed (inter-row)		21
Raised bed (within row)		22

At Karnal, no clear differences in relative distribution of beads between tillage systems were observed. Standard errors for the means were large, which is likely to be related to the ploughing and puddling operations associated with the summer rice cultivation. The aim of puddling is to destroy soil aggregates and disperse fine clay articles, so that a dense zone at the base of the puddled layer is formed, which restricts water loss through percolation and improves rice growing conditions. It is obvious that puddling has a strong effect on the relative distribution of beads throughout the soil profile, resulting in extensive vertical movements. Puddling resulted in extensive horizontal movement of beads as well. This explains why at Hisar between 61 and 91% of the beads were recovered, while recovery rate at Karnal did not exceed 22% [Table 2.5]. Low recovery rates resulted in relatively large variation in numbers of recovered beads within treatments, giving high standard errors.

Therefore, no conclusions were drawn on the effect of different wheat tillage systems in rice-wheat rotations on the movement of beads.

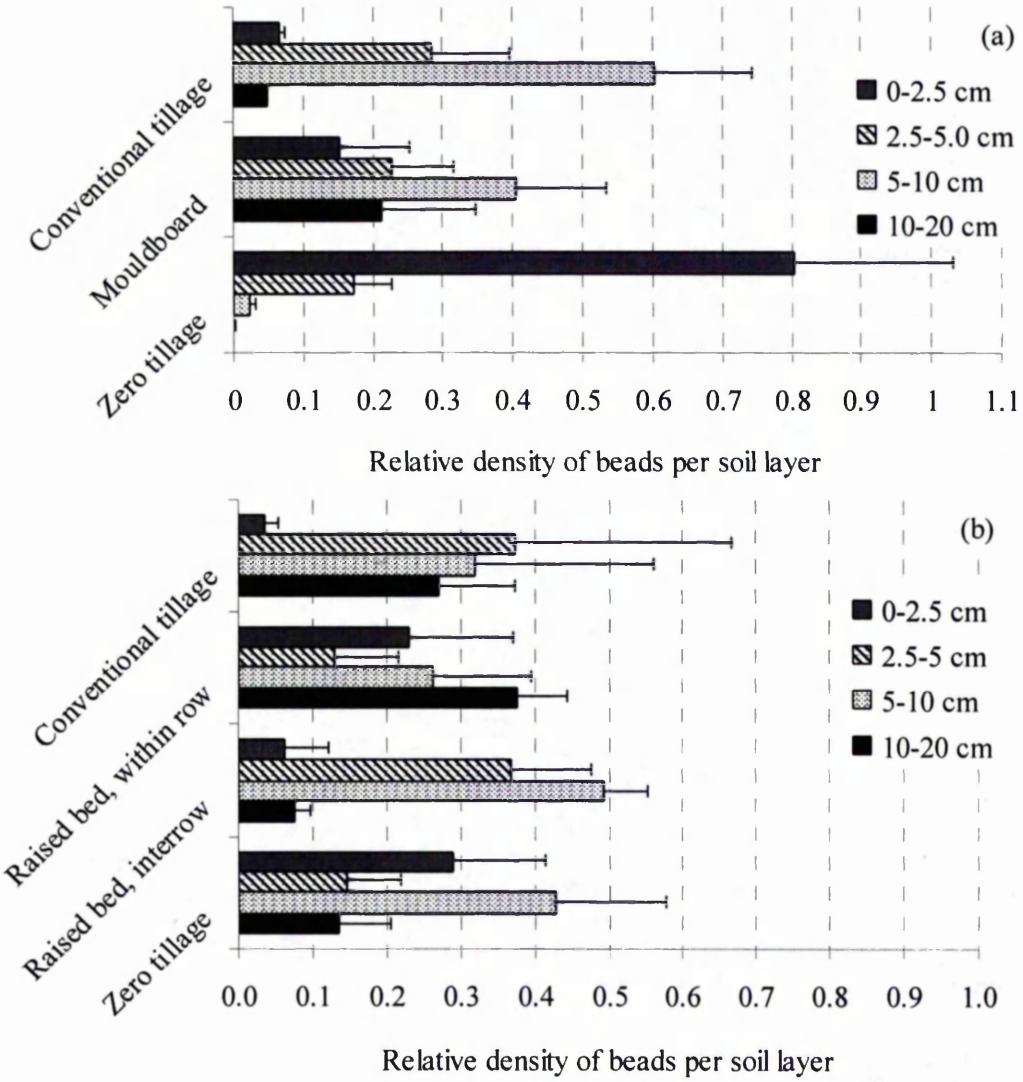


Figure 2.5 Effects of soil cultivation techniques before wheat sowing on the relative distribution of beads in (a) a millet-wheat at Hisar and (b) a rice-wheat rotation at Karnal.

The movement of beads as affected by different tillage systems can be compared with the movement of recently shed *P. minor* seeds. As *P. minor* seed longevity under field conditions is limited with half-lifes usually less than one year, the fate of recently shed *P. minor* seeds contribute most to the relative distribution of the entire seedbank. Moss [1998] found that the effect of cultivation on burial of seeds and plastic beads varied little between experiments on a range of soils in different years. Cousens & Moss [1990] mentioned that most of the inversion of soil by a plough is by bulk movement in a relatively uniform way. Seeds are thus likely to move with the soil, relatively independently of their size and shape. Therefore, bead movement as affected by various tillage systems, observed at Hisar, may well reflect the movement of recently shed *P. minor* seeds in similar tillage systems. In rice-wheat systems however, puddling operations disperse fine clay particles along with seeds through water. Afterwards, clay particles and seeds are allowed to settle. Seed size, shape and specific gravity, relative to clay particles and water, are important factors determining how soil and seeds settle down in the newly formed soil profile after puddling. Beads that do not closely approach the size and specific gravity of seeds are not suitable to mimic the movement of seeds as affected by puddling. Therefore, the use of real seeds instead of beads may be preferred here.

2.3.2.2 Seed and soil settling experiments

The experimentally determined average terminal velocity of *P. minor* seeds in water of 30^0C was 0.040m s^{-1} (9.7 E-04). According to Stokes' law, the terminal velocity of *P. minor* seeds equalled that of gravel of 5.8mm in diameter [Figure 2.6]. In Haryana, rice is cultivated on clay, clay loam and silty clay loam. The physical breakdown of soils from two locations under rice-wheat is presented in Appendix I, showing that 98% of the soil mass consisted of soil particles smaller than 0.125mm. The results thus suggested that after puddling *P. minor* seeds settle quicker than most soil particles, which may lead to an accumulation of seeds in the lower layers of resettled soil.

The puddling experiment however, aiming to mimic the effects of puddling on soil and seed settling in a beaker, suggested an entirely different settling behaviour. After soil disturbance, more than 50% of the seeds were found in the upper 0.5cm of the soil, while less than 5% of the seeds were recovered below 2cm [Figure 2.7], suggesting that puddling causes an accumulation of seeds in the upper layer of the soils. The difference in outcome between the two experiments could be related to the conditions under which Stokes' law is valid. Stokes' law assumes the falling object is a perfect sphere, which is not the case for soil particles. In addition, the viscosity of water increases when in suspension with soil particles, slowing down the settling rate of soil particles. Another explanation for the differences in outcome is that few *P. minor* seeds reached their terminal velocity in the second experiment. It was observed that many seeds floated on the water surface before settling down. Other seeds adhered to air bubbles or to the walls of the beaker slowing down their settling velocity. As the second experiment more closely resembled the field conditions during puddling, its results may be more reliable than the outcome from the first experiment.

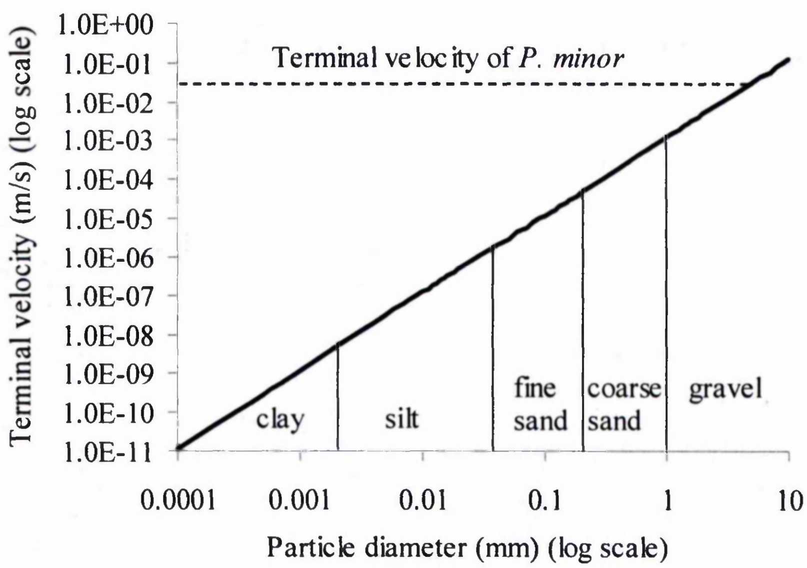


Figure 2.6 Settling velocity of free falling soil particles classified according to the Soil Survey of Engeland and Wales [White, 1979], in comparison with the settling velocity of *P. minor* seeds.

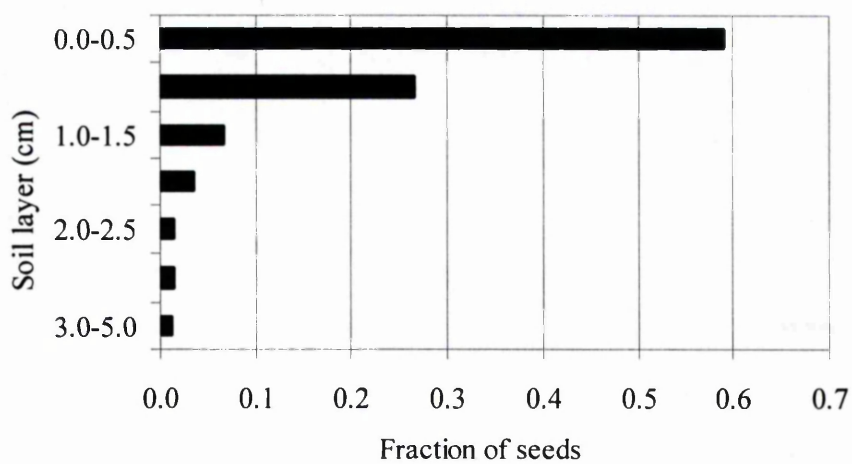


Figure 2.7 Settling behaviour of *P. minor* seeds with soil after disturbance in a beaker.

2.3.3 Straw burning studies

2.3.3.1 Oven experiment

Exposure of seeds to different temperature/time combinations in the oven demonstrated that the higher the temperature, the quicker seeds were killed ($F_{pr}<0.001$) [Table 2.6]. Furthermore, it was found that imbibed seeds were more sensitive to heat than dry seeds ($F_{pr}<0.001$). At 200^{0}C, it took 220s to kill 50% of the dry seeds, while it took less than 30s to kill 50% of the imbibed seeds. Dry seeds were well capable of surviving temperatures up to 150^{0}C, while imbibed seeds began to loose their viability at temperatures over 75^{0}C. Average germination rate of dry and imbibed seeds in the control treatment was respectively 97 and 93%, which is close to the germination rates of seeds exposed to 50 or 75^{0}C. No significant differences in germination behaviour between IPU-susceptible and resistant seeds were observed. The experiment indicated that seeds in the soil could easily survive temperatures up to 75^{0}C for at least 300s. In addition, it suggested that straw burning at a time when soil moisture conditions are suitable for *P. minor* germination may benefit the control rate of burning.

Table 2.6 Time (s) required to kill 50% of *P. minor* seeds at various temperatures in the oven.

Temperature (^{0}C)	Dry seed	Imbibed seed
50	>600	>600
75	>600	>600
100	>600	170
150	580	150
200	220	<30

2.3.3.2 Straw burning field experiments

Temperature recordings conducted during the second burning experiment (Study 2) showed that doubling the straw quantity from 6 to 12t ha^{-1} did not significantly change soil temperatures at most recording times [Figure 2.8 and Table 2.7]. Only at 90s and beyond 360s after initiation of straw burning, temperature differences between straw quantities were significant. Variability in recorded soil temperature was high, probably due to irregular heat development during burning. Beyond 360s, when the heat had more uniformly spread through the soil profile, variability in soil temperature was reduced and differences between straw treatments became significant. *P. minor* germination rates reflected the temperature recordings and were not strongly affected by the quantity of burned straw [Figures 2.9, 2.10 and Table 2.7]. While increasing the quantity of burned straw had a slight effect on seed germinability in Study 1, especially when seeds were buried at 1 and 2cm, there was no such effect visible in Study 2.

Depth of burial, unsurprisingly, did have a strong influence on the recorded temperature course. Near the surface, temperatures during burning rapidly reached their maximum and the soil cooled down quickly afterwards. At the soil surface, temperatures up to 600^0C were recorded. At 1cm, maximum-recorded soil temperature was only 75^0C; at 2 and 4cm, temperatures did not exceed 35^0C. Accordingly, germinability of seeds was strongly affected by depth of burial. In both studies, seeds on the surface were all burned and charred and completely lost their viability. Seeds buried at 1cm lost germinability compared with seeds buried at lower depths. As variation in recorded soil temperature at 1cm was large, seed survival at this depth strongly depended on chance factors; *i.e.* how much heat was produced on top of the seed and how well seeds were protected against strong heat.

Rice straw burning before wheat sowing has been related to increased germinability and emergence of *P. minor* and reduced herbicide efficacy [Singh *et al.*, 1999b]. The present burning and oven studies provided no evidence that *P. minor* seeds receiving a mild heat shock germinate better than seeds stored under laboratory conditions. This suggests that studies reporting enhanced germination and emergence after straw burning reflect a better environment for germination after burning, rather than a real stimulation of the seeds. A similar suggestion was made by Moss [1980], studying the effects of straw burning on seed germination and emergence of *Alopecurus myosuroides*.

Farmers do not spread out straw uniformly over the field before burning and the burning process itself is irregular and patchy. Consequently, some spots will be more affected by burning than others. In the present experiments, the impact of doubling the straw quantity on seed survival was rather modest. It is expected that irregular, patchy burning allows many seeds on the surface to survive at spots where no burning occurred, while seeds covered by soil are little affected at spots where strong burning occurred. Consequently, overall effectiveness of burning as a weed control tool is likely to be reduced by irregular, patchy burning. This hypothesis is further examined in the section below.

For the rice-wheat system in Haryana, it is concluded that wheat straw burning in spring may kill many recently shed *P. minor* seeds at the soil surface. The impact of wheat straw burning in spring on the germination environment of *P. minor* in autumn will be negligible. Wheat straw burning is however not often practised in Haryana, because wheat straw is a valuable product that is used as cattle fodder, building material or sold at local markets. After the summer rice crop, the majority of the *P. minor* seeds are buried deeper than 1cm from the surface. The impact of rice straw burning in autumn on *P. minor* mortality is likely to be small, while the environment for *P. minor* germination may be improved and herbicide efficiency may be reduced. Therefore, prospects for using straw burning for *P. minor* control are limited within the rice-wheat system.

Table 2.7 Effect of soil depth on temperature recorded after initiation of straw burning, F_{pr} as calculated by ANOVA.

Time (s)	*Straw*	*Depth*	*Time (s)*	*Straw*	*Depth*
0	0.599	*<0.001*	240	0.183	*<0.001*
30	0.173	*<0.001*	*270*	0.152	*<0.001*
60	0.209	*<0.001*	*300*	0.694	*<0.001*
90	*0.046*	*<0.001*	*330*	0.122	*<0.001*
120	0.157	*<0.001*	*360*	0.120	*<0.001*
150	0.542	*<0.001*	*390*	*0.012*	*<0.001*
180	0.366	*<0.001*	*420*	*0.048*	*<0.001*
210	0.260	*<0.001*	*450*	*0.001*	*<0.001*

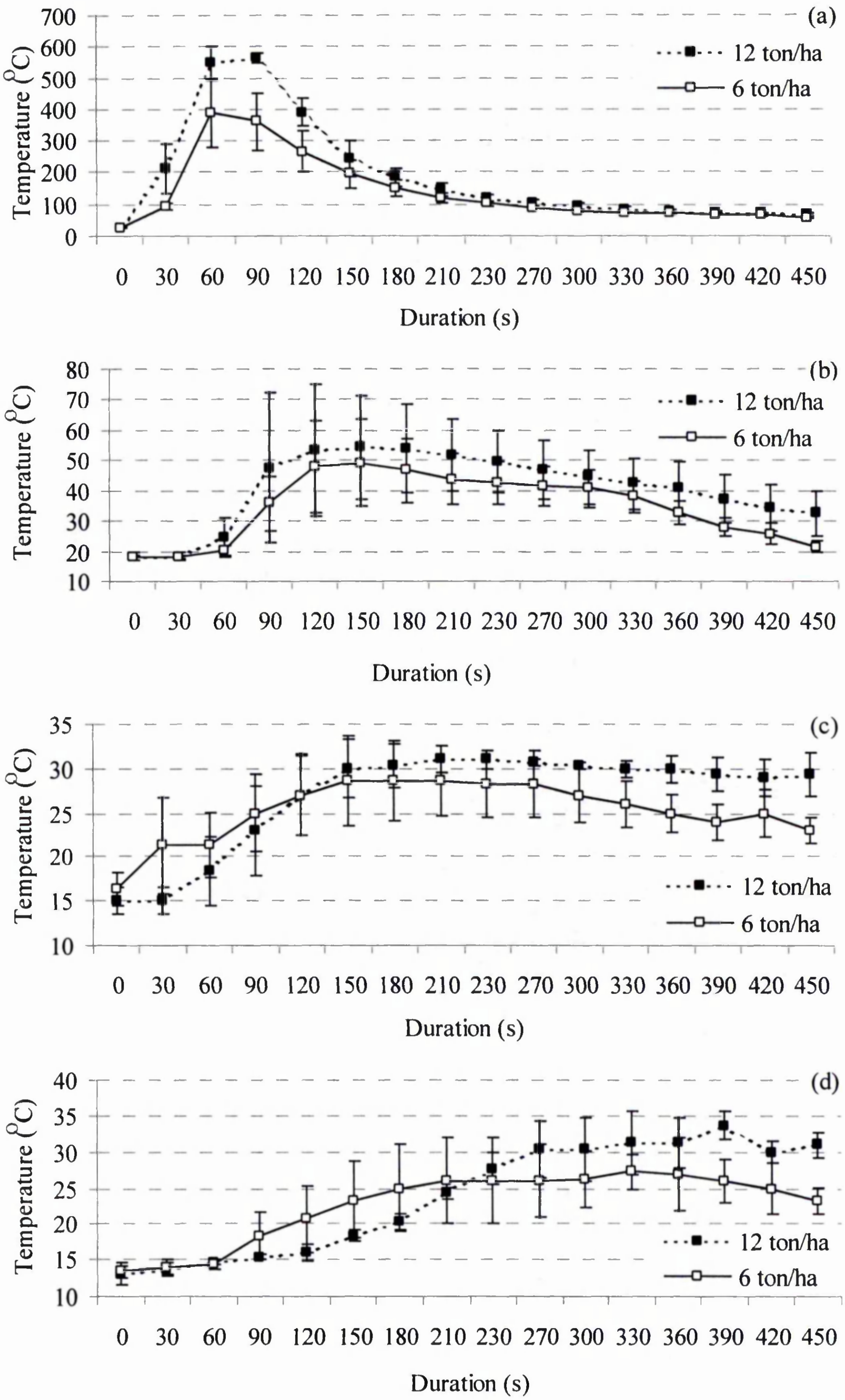


Figure 2.8 Soil temperature course at (a) the soil surface, (b) 1cm, (c) 2cm and (d) 4cm during burning of 6 or 12t wheat straw ha^{-1} in Study 2.

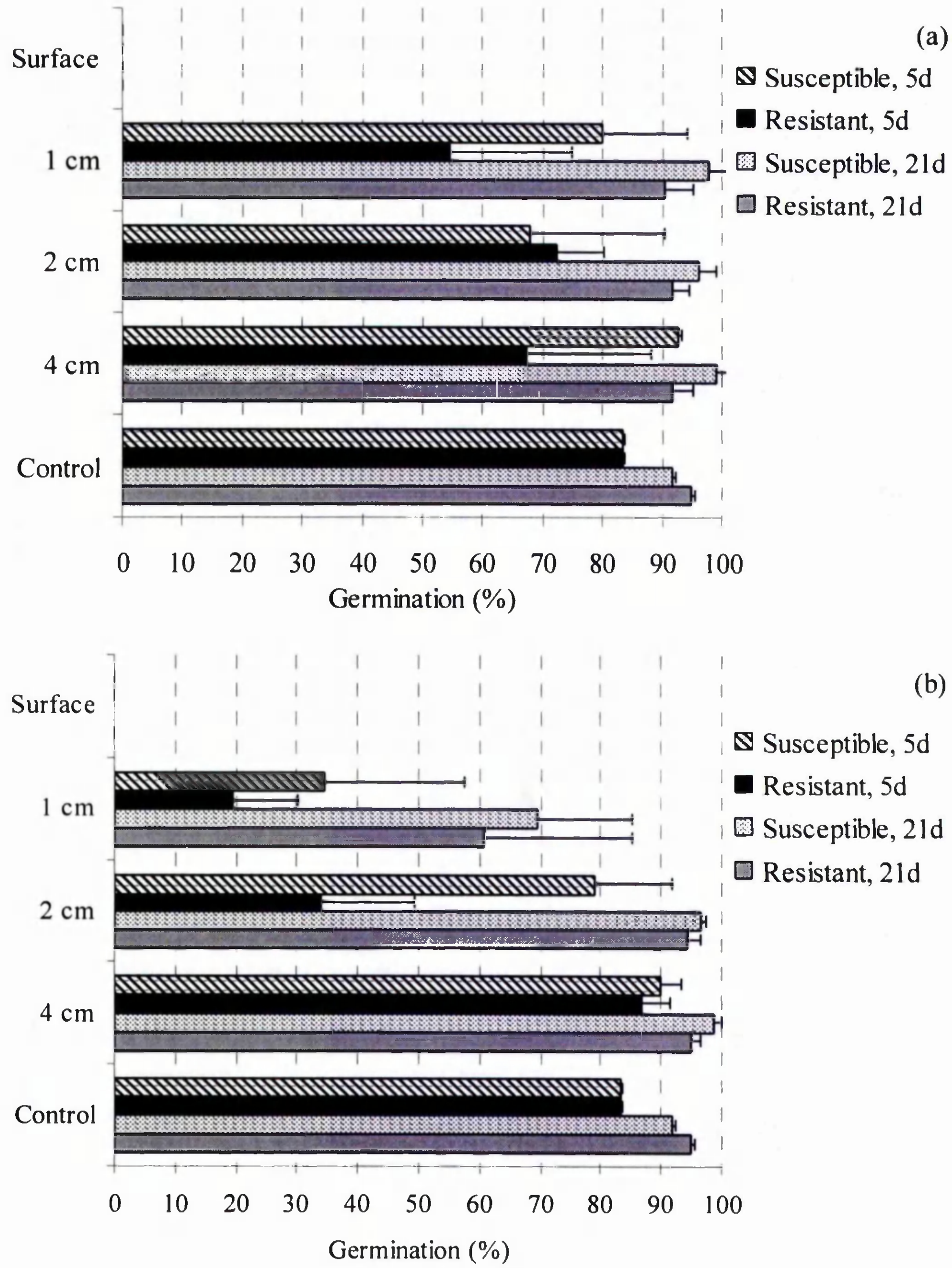


Figure 2.9 Effect of depth of burial on seed germinability after burning (a) 6t ha^{-1} and (b) 12t ha^{-1} of rice straw, assessed after 5 and 21 days in incubator (Study 1).

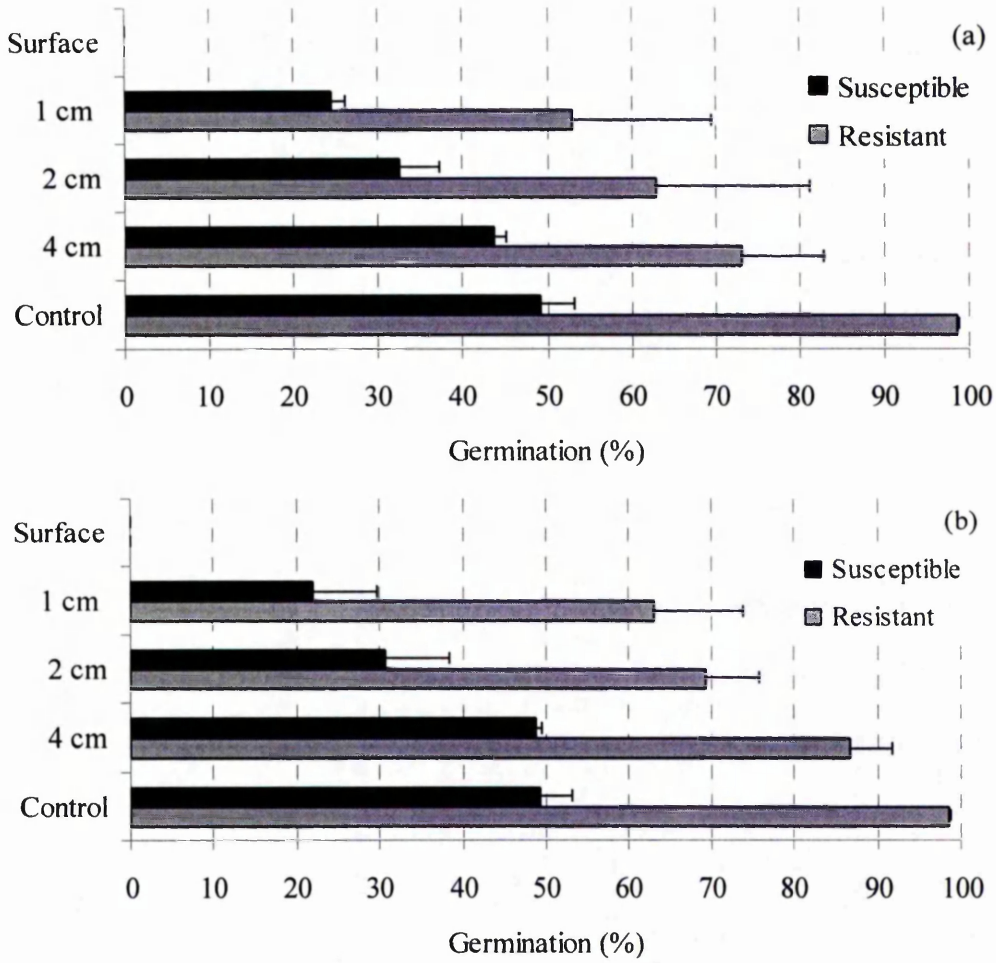


Figure 2.10 Effect of depth of burial on seed germinability after burning (a) 6t ha^{-1} and (b) 12t ha^{-1} of wheat straw (Study 2).

2.3.3.3 Straw burning model: construction and performance

With a simulation model, the validity of the previously mentioned hypothesis, that patchy burning, *i.e.* burning of higher straw quantities in smaller areas, reduces the overall effectiveness of burning as a way to kill *P. minor* seeds, has been further explored. By calculating seed mortality rates for each soil layer after burning, the effect of patchy burning on the total seed mortality can be calculated for various seed distribution patterns. The model assumed that the germination rates, experimentally observed at various soil depths, represent the germination rate in the soil layer above this depth up to the next depth where germination was measured. For example, germination rate at 2cm represents in the model the germination rate for seeds buried in the layer 1-2cm. The average germination rates observed in the two burning experiments and the control treatments were used to calculate seed mortality rate for 6 and 12t straw ha^{-1} for seeds buried at 0, 1, 2 and 4cm [Table 2.8]:

$$mr_{k,s} = \frac{gr_{control} - gr_{k,s}}{gr_{control}} \quad (2.1)$$

Where:

$mr_{k,s}$ Mortality rate of seeds in soil layer k after burning straw quantity s.

$gr_{k,s}$ Average germination rate in soil layer k after burning straw quantity s.

$gr_{control}$ Average germination rate of the control treatment.

Value for k is 0, 1, 2 or 4, representing the soil layers: surface, 0-1, 1-2 and 2-4cm, respectively. Value for s is 6 or 12, representing 6 and 12t straw ha^{-1} respectively.

Table 2.8 Seed mortality rates at four soil depths for two straw quantities.

Depth (cm)	*6t ha^{-1}*	*12t ha^{-1}*
0	1.	1.
1	0.23	0.36
2	0.17	0.16
4	0.10	0.04

Seed mortality of a particular soil layer is calculated by multiplying the mortality rate with the number of seeds in that layer. Total seed mortality in the upper 4cm is the sum of the seed mortality of each layer:

$$m_{tot,s} = \sum_{k=0,1,2,4} \left(mr_{k,s} \cdot d_k \right) \quad (2.2)$$

Where:

$m_{tot,s}$ Number of seeds killed in the upper 4cm of the soil after burning straw quantity s.

d_k Seed density per unit area of measurement in soil layer k.

Overall mortality rate (mr_{tot}) can be calculated as the ratio of the total number of seeds killed after burning in the upper 4cm to the total number of seeds present in the upper 4cm of the soil:

$$mr_{tot,s} = \frac{\sum_{k=0,1,2,4}(mr_{k,s} \cdot d_k)}{\sum_{k=0,1,2,4} d_k} \qquad (2.3)$$

It is assumed that the presence of 12t straw ha^{-1} (double the normal quantity) is the result of piling up straw in half the field, while the other half of the field remains unburned. Average mortality rate of the entire field is consequently reduced by 50%. Equation 2.3 should be adjusted as follows:

$$mr_{tot,s(field)} = \frac{\sum_{k=0,1,2,4}(mr_{k,s} \cdot d_k)}{\sum_{k=0,1,2,4} d_k} \cdot \frac{A_b}{A_{tot}} \qquad (2.4)$$

Where:

$mr_{tot,s(field)}$ Field average of seed mortality rate in the upper 4cm soil after burning s ton straw ha^{-1}.

A_b Area of the field under burning.

A_{tot} Total area of the field.

To examine the model's performance, estimations of the relative vertical distribution of seeds throughout the upper 4cm of the soil profile are required. Directly after *P. minor* seed shed in April, the majority of the newly shed seeds are located close to the surface. In the model it is assumed that, during burning in spring, 50% of the seeds are located at the soil surface, 25% of the seeds in soil layer 0-1cm, while the remaining seeds in layers 1-4cm are equally spread over these layers. Before wheat sowing in October, relative distribution of *P. minor* seeds throughout the soil profile will be different. In the model it is assumed that, during burning in autumn, 10% of the seeds are located on the soil surface, while the remaining 90% of the seeds are equally distributed over the upper 4cm of the soil.

Using equations 2.1 to 2.4, seed mortality rates of areas where straw is burned and the average mortality rate of the entire field can be calculated [Table 2.9]. The results generated by the model indicate that spring burning is more effective than autumn burning due to differences in relative distribution of seeds throughout the soil profile. In addition, the results indicate that highest mortality rates are obtained when straw is equally dispersed over the entire field. Patchy burning of higher straw quantities reduces the overall effectiveness of burning as a way to kill *P. minor* seed. The effect of doubling the straw quantity on seed mortality rate in burned plots is marginal, and fails to compensate for increased seed survival in plots that are not subject to burning.

Table 2.9 Effect of spring and autumn burning on seed mortality rate at burning spots and average of the entire field, as calculated by a simulation model.

	Burned area		*Entire field*	
Time of burning	*6t ha^{-1}*	*12t ha^{-1}*	*6t ha^{-1}*	*12t ha^{-1}*
Spring	0.59	0.61	0.59	0.31
Autumn	0.24	0.24	0.24	0.12

CHAPTER 3: LIFECYCLE STUDIES

3.1 Introduction

3.1.1 Aims of the experiment

Without thorough knowledge of the lifecycle of *P. minor*, it is difficult to assess how *P. minor* populations are affected by weed control practices in subsequent years and how new weed control strategies can be optimally utilised. Practical experience in Haryana has demonstrated that application of zero tillage systems results in reduced numbers of emerged seedlings of *P. minor*, but the mechanism behind this observed reduction is largely unknown. Therefore, the long-term effects of zero tillage on weed population dynamics are still uncertain. Under experimental conditions, alternative herbicides have shown the potential to give almost complete control of IPU-resistant *P. minor* [Brar & Singh, 1997; Walia & Brar, 1996]. In farmers' fields however, this control rate is rarely obtained. To improve herbicide control rate in farmers' fields, better understanding is required how these herbicides affect survival chances and growth rate of various *P. minor* flushes and how they affect crop-weed interactions later in the season. Therefore, a field experiment was carried out to assess the effects of tillage systems and herbicides on the population dynamics of *P. minor*.

The present field experiment was conducted with the following objectives:

(i) to study how zero tillage, compared with conventional tillage, affects distribution of *P. minor* seeds through the soil profile, *P. minor* emergence and growth and final wheat yield;

(ii) to investigate the effects of herbicide application on *P. minor* densities and plant weight as well as final wheat and *P. minor* yield;

(iii) to quantify the relationship between *P. minor* plant size and reproductive output.

3.1.2 Seedbank sampling and seedling emergence

One of the aims of the experiment was to quantify the relationship between soil seedbank composition and emergence rate in conventional and zero tillage systems. Reliably estimating soil seedbank populations is often problematic, because of large variations in soil seedbank composition within fields and the difficulty in accurately assessing the number of viable seeds in soil samples. Methods for estimating soil seedbank densities can be differentiated into two classes (Gross, 1990). In the first class of methods, seeds are separated physically from the soil through sieving, washing, elutriation, centrifugation, air separation or flotation of seeds in salt solutions, for which various methodologies have been developed [Thorsen & Crabtree, 1977; Smucker *et al.*, 1982; Gross & Renner, 1989; Ball & Miller, 1989]. The alternative method is to place soil samples in suitable germination conditions and subsequently, to assess the number of emerged seedlings. The latter class of methods is often called germination methods [Roberts, 1981]. The first class of methods has the disadvantage of overestimating the number of viable seeds in the soil, because non-viable seeds are included. The alternative class of methods tends to underestimate the soil seedbank density, as some viable seeds may not germinate and are therefore not included in the assessment of the seedbank. Bàrberi *et al.* [1998], Forcella [1992] and Gross [1990] compared the potential of these methods to predict seedling populations and concluded that assessing the soil seedbank through germination methods was a more reliable way to estimate seedling populations than seed extraction methods. Cardina & Sparrows [1996] and Ball & Miller [1989] on the other hand, concluded no class of methods gave consistently higher correlations between seedbank estimates and seedling density for various years and tillage systems. Moreover, both studies concluded that the predictive value of data on seedbank composition for seedling emergence estimation is relatively poor in both methods.

Predictions of weed seedling populations based on seedbank densities are often poor, because estimations of seedbank composition lack accuracy and because of a large variation in emergence rate between years and tillage systems. This variation is difficult to predict, because the complex processes in the soil related to seedbank dynamics are difficult to monitor and complete data sets relating soil seedbank densities with seedling emergence, in which all relevant environmental parameters have been monitored, are still lacking. An accurate prediction of seed dormancy under field conditions is also missing [Kropff *et al.*, 1996]. Zhang *et al.* [1998] aimed to improve weed seedling population predictions by correlating seedling populations to the active soil seedbank. Active seeds are those seeds that are germinable at the time of sampling excluding seeds that were originally dormant, but released from dormancy by disturbances to the soil during germination tests. In Zhang's study, correlation coefficients between the active soil seedbank and the number of emerged seedling were however within the same range as most other studies using standard germination methods (between 0.25 and 0.60). Another possibility for improving weed seedling estimates is to divide the soil into various horizontal layers. Seed germination and emergence rates are strongly affected by depth of burial, which may partly explain the large differences in emergence rate between different tillage systems. Despite the importance of depth of burial of seeds in determining seedling emergence, only few studies have accounted for the vertical distribution of weed seeds throughout the soil profile [Mohler, 1993].

3.2 Materials & Methods

The field studies were conducted at two farmers' fields at different locations in Haryana, India: one experiment was carried out near the village of Pirthala (Fatehabad district) in winter 2000-2001; a second experiment was conducted near the village of Narnaund (Hisar district), in winter 2001-2002 [Table 3.1]. The soil type was silty clay loam at both locations. Soil analyses, carried out by the SAC central analytical laboratory on samples taken from both fields, are given in Appendix I. Both fields had been under continuous rice-wheat rotation for more than five years before the start of the experiment and had no history of zero-tillage usage. At both locations, the soil contained a high natural seedbank of IPU-resistant *P. minor* and no extra seeds were added to the soil before the start of the experiment.

Experimental layout. The experimental fields were equally divided over four replicate blocks [Figure 3.1]. Treatments were arranged in a split-plot design. Each block was split into two plots that were either conventionally tilled or under zero tillage. Plots in turn were split into five subplots, each subplot receiving a different weed control treatment. The total size of the field at Pirthala was 1.4ha and the size of each subplot was 6x60m; the total size of the field at Narnaund was 0.8ha and the size of each subplot was 15x13m.

Ploughing and sowing. Plots under conventional tillage were ploughed twice with a local disk plough (10-15cm deep), harrowed twice, and then planked. Planking is a standard cultivation practice in this region, which involves the soil being flattened by a heavy baton (often with extra weights added) being drawn over the soil surface. Wheat seeds were sown using a standard seed drill. Fields under zero tillage received no soil cultivations at all prior to sowing. Wheat seeds were directly drilled into the stubbles of the previous rice-crop with a zero-till drill. At Pirthala, wheat variety PBW343 was sown Nov. 20-21, 2001; at Narnaund, the same variety was sown Nov. 17-18, 2002. At both locations, wheat was sown using 125kg seed ha^{-1} and a row separation of 20cm.

Table 3.1 Details of the experimental set-up of the two *P. minor* lifecycle studies.

	Study 1	*Study 2*
Nearest village	Pirthala	Narnaund
District	Fatehabad	Hisar
State	Haryana	Haryana
Soil Type	Silty clay loam	Silty clay loam
Season	2000-2001	2001-2002
Total field size	1.4ha	0.8ha
Plot size	6 x 60m	15 x 13.3m
Soil sampling	Nov 17-19	Nov 11-12, 14-15
Sowing	Nov 20-21	Nov 17-19
Irrigations	Dec 18, Jan 22, March 5, March 26	Feb 12 Dec 24, Jan 22 Feb 25, March 18
Seedling assessment	Dec 26	Jan 3
Herbicide spraying	Dec 26, Jan 7	Jan 7-8
Mid-season harvest	Feb 15-16	Feb 22-23
Final harvest	April 10-11	April 9-10

Weed control. Each subplot received one of the following weed control treatments: no weed control, isoproturon (1250g a.i. ha^{-1}, Gharda Chemicals Ltd) sulfosulfuron (25g a.i. ha^{-1}, Monsanto), clodinafop-propargyl (60g a.i. ha^{-1}, Syngenta India Ltd) or fenoxaprop-P-ethyl (120g a.i. ha^{-1}, Rhone-Poulenc). Herbicides were applied at Pirthala on Dec. 26, 2000, (isoproturon) and Jan. 7, 2001, (other herbicides) and at Narnaund on Jan. 7-8, 2002 (all herbicides). Herbicides were applied at recommended rates and recommended weed growth stage using a knapsack sprayer with a flat fan nozzle, which is common practice in the region.

Fertilisation and irrigation. Before sowing, 125kg urea ha^{-1} was manually broadcast in the fields (1kg urea contains 0.46kg nitrogen). After the first irrigation, another 125kg urea ha^{-1} and 125 kg di-ammonium-phosphate ha^{-1} was applied (1kg di-ammonium-phosphate contains 0.20kg phosphate and 0.18kg nitrogen). In total, 137.5kg nitrogen ha^{-1} and 25kg phosphate ha^{-}

[1] were added during the wheat cultivation. No other nutrients were applied. Irrigation was conducted at Pirthala in the weeks of Dec. 18, 2000, Jan. 22, Feb. 12, March 5 and March 26, 2001; at Narnaund in the weeks of Dec. 24, 2001, Jan. 22, Feb. 25 and March 18, 2002.

Seedbank sampling. To assess the *P. minor* seedbank, five sampling points were marked in each tillage plot. At each measuring point, five soil samples were taken after soil cultivation, before wheat sowing, with a soil auger, 8.6cm in diameter and 20cm deep. Total soil volume per sampling point was $5809cm^3$. Soil samples were split into the soil layers 0-2.5, 2.5-5, 5-10 and 10-20cm. At HAU, Hisar, seeds and organic matter were separated from the soil by washing through 1.0mm wide sieves. Seeds, mixed with the remaining organic matter, were allowed to germinate in Petri dishes in an incubator at 15^0C with continuous light. The readily germinable fraction of the *P. minor* seeds in the soil samples was estimated by counting the number of emerged seedlings in the Petri dishes. After four weeks, the first assessment was done and seedlings were removed. Subsequently, soil samples were removed from the incubator, dried at room temperature for one week, mechanically kneaded, wetted again and placed back into the incubator. A second assessment was made eight weeks after sampling. In the field, *P. minor* seedling emergence was counted at 39 (Pirthala) and 45 (Narnaund) DAS. Seedling emergence of 1^{st} and 2^{nd} flush was assessed in two quadrats of $0.25m^2$ at each measuring point in the field. At Narnaund, only the first flush of seedlings was assessed.

Plant growth measurements. The effect of the weed control treatments on plant-weed interaction was assessed in February (midseason harvest) and in April (final harvest). After herbicide application, in each weed control subplot, two new measuring points were marked. Midseason harvest was conducted at Pirthala on Feb. 15-16, 2001, and at Narnaund on Feb. 22-23, 2002. *P. minor* density of 1^{st} , 2^{nd} and 3^{rd} flush was determined in two quadrats of $0.25m^2$ at each new measuring point. In both quadrats, aboveground plant parts of the three *P.*

minor flushes and wheat were harvested. At Narnaund, the three *P. minor* flushes were harvested separately; at Pirthala only total *P. minor* biomass was determined. At HAU, Hisar, plant samples were sun dried for 1 week, oven dried (70^0C) for 48h and subsequently dry matter weight was determined. Final *P. minor* and wheat densities and biomass were assessed at Pirthala on April 10-11, 2001, and at Narnaund on April 9-10, 2002. *P. minor* density and biomass was determined at each measuring point in two quadrats of $0.25m^2$. At final harvest, various *P. minor* flushes could no longer be distinguished and were therefore not separated. At HAU, plant samples were oven dried (70^0C) for 48h and weighed. Wheat grain yield and harvest index were assessed by harvesting $1m^2$ wheat at each measuring point. At HAU, wheat samples were threshed and grain and straw yield were determined.

Seed production. To assess the relationship between plant size and reproductive output, 26 *P. minor* plants at Pirthala and 29 plants at Narnaund were randomly selected in the experimental fields. The plants' flowering heads were covered with small paper bags three weeks before wheat harvest to prevent seed losses. At harvest time, aboveground parts of these plants were removed. In the laboratory, seeds were extracted from the ear heads and weighed. Thousand seed weight was assessed by counting the number of seeds of a weighed sample from each plant's seed production. Remaining plant material was oven-dried at 70^0C for 48h and weighed. Seeds collected at Pirthala in April 2001 were stored under laboratory conditions for eight months and their germinability was tested at SAC, Ayr, in December 2001. Sixty seeds per plant were allowed to germinate in 3 Petri dishes (20 seeds $dish^{-1}$) on moisturised paper in an incubator at 15^0C, 11h daylight. The Petri dishes were placed in the incubator for 21d and during this period, paper in the dishes was kept moist. After 21d, germinability was assessed.

Data analysis. Treatment effects were studied with ANOVA. Linear and non-linear regression methods were used to study the relationship between variables. Survival rate of *P. minor* seedlings until midseason harvest was calculated as the ratio of 1st and 2nd flush seedling density, as assessed early in the growing season, to the density of 1st and 2nd flush plants at midseason. Survival rate of *P. minor* plants from midseason until final harvest was estimated using multiple regression analysis correlating 1st, 2nd and 3rd flush plant densities at midseason harvest with final plant density. Data from all tillage/herbicide treatments were lumped together in the multiple regression analysis, as the number of data points per treatment was too small to conduct a regression analysis for each individual treatment.

The relationship between final *P. minor* density and wheat yield reduction was quantified using a rectangular hyperbola, as described by Cousens [1985a]. The use of this model was justified since it is a semi-mechanistic model requiring only two input parameters and the high variance in the data did not allow the application of more complex weed-yield loss models. The mathematical expression of the applied model is as follows:

$$Yl = \frac{I \cdot d}{1 + \frac{I}{A} \cdot d}$$

Yl percentage yield loss

d density of weed

I percentage yield loss per unit weed density as $d \rightarrow 0$

A percentage yield loss as $d \rightarrow \infty$

Percentage yield loss relates to the gap between maximum yield under weed-free condition and the actual yield. In the two experiments, maximum yield under weed free conditions was considered equal to the average yield in sulfosulfuron-treated fields, where *P. minor* densities and biomass were close to zero.

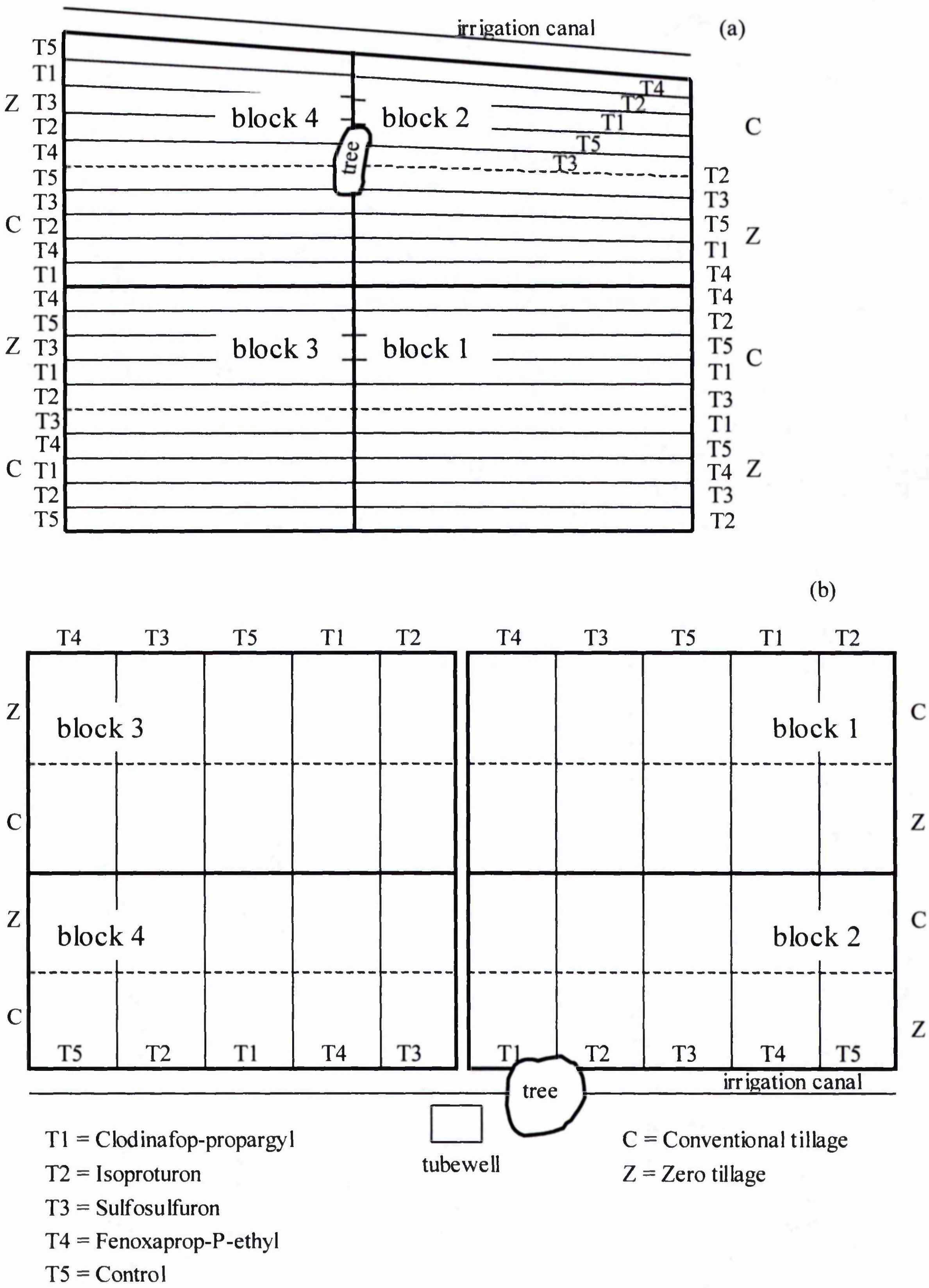


Figure 3.1 Layout of the experimental fields nearby (a) Pirthala and (b) Narnaud village.

3.3 Results & Discussion

3.3.1 Seedbank composition

At Pirthala, no significant difference were found in *P. minor* seedbank density or relative vertical distribution of the seeds throughout the soil profile between conventional and zero tillage [Figure 3.2a]. Seeds were relatively equally distributed over the upper 10cm of the soil in both tillage systems, probably as a result of extensive tillage operations associated with the preceding rice cultivation. Few seeds were found below 10cm deep in both tillage systems, indicating that local disc ploughs and puddling machinery at Pirthala did not disturb the soil below 10cm.

At Narnaund, average *P. minor* soil seed density was 3.3 times higher than at Pirthala [Figure 3.2b]. Furthermore, ANOVA showed that plots under zero tillage contained more seeds than plots under conventional tillage (F_{pr} [tillage]<0.001). Conventional tillage operations prior to wheat sowing were unlikely to remove a significant number of *P. minor* seeds from the plots under conventional tillage. Therefore, this difference in seed density was probably reflecting an unequal spatial distribution of weed seeds throughout the field before the start of the experiment, rather than an immediate effect of tillage on the total number of seeds in the soil. Also the relative distribution of seeds over the four soil layers varied between the two tillage systems (F_{pr} [tillage x layer]<0.001). Tillage regime could have an immediate impact on the relative vertical distribution of seeds [Clements *et al.*, 1996]. Under conventional tillage, a larger proportion of seeds were found below 10cm than under zero tillage, suggesting that the soil cultivations at Narnaund caused more disturbance in the lower soil layers than at Pirthala.

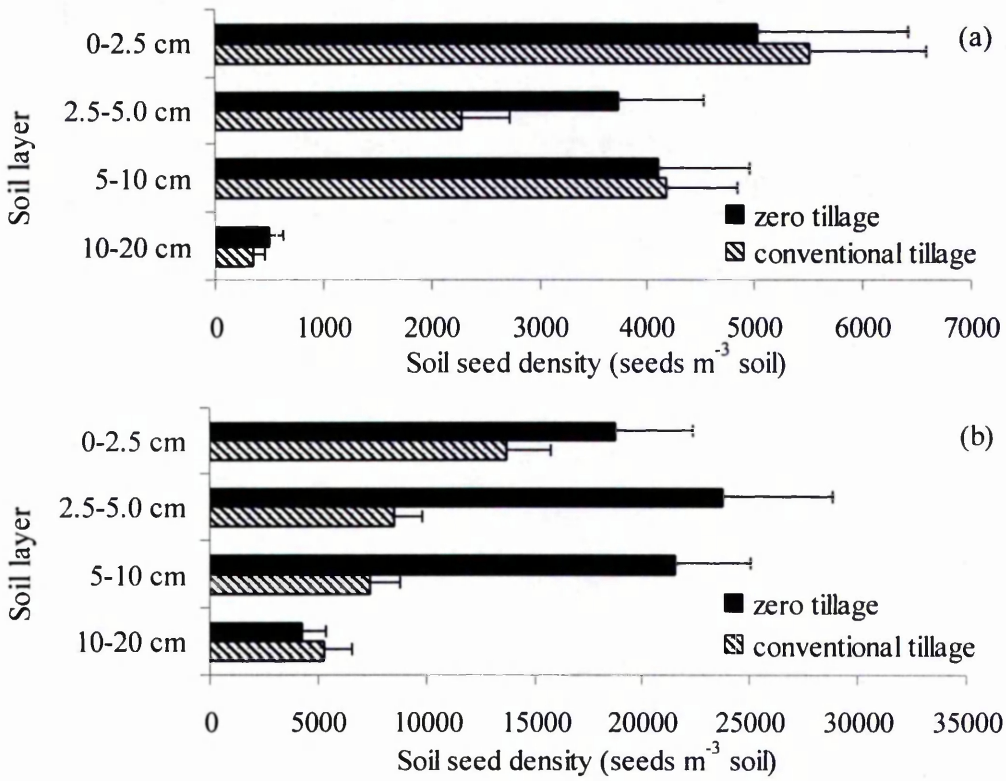


Figure 3.2 Relative distribution of *P. minor* seeds throughout the soil profile after zero tillage and conventional tillage at (a) Pirthala and (b) Narnaund.

3.3.2 Seedling emergence

Zero tillage reduced the emergence rate of *P. minor* during the 1st, 2nd and 3rd flush of germination, as compared with conventional tillage [Figure 3.3]. Differences between the two tillage systems in emergence rate were found significant for most treatments [Table 3.2]. Simple linear regression analysis, correlating the number of seeds in the soil with the number of emerged seedlings, indicated that zero tillage reduced the emergence rate of *P. minor* of the 1st flush by around 50%. Only seeds in the upper 10cm of the soil were included in the regression analysis, as it is known from literature that *P. minor* seedlings fail to emerge if buried deeper than 10cm [Chhokar *et al.*, 1999; Okereke *et al.*, 1993]. Emergence rates during the 1st and 3rd flush of germination varied little between Pirthala and Narnaund. As soil seed densities were higher at Narnaund and emergence rates were equal at both locations, seedling density at Narnaund exceeded that of Pirthala.

Table 3.2 The effect of tillage regime on *P. minor* emergence rate (F_{pr} as calculated by ANOVA).

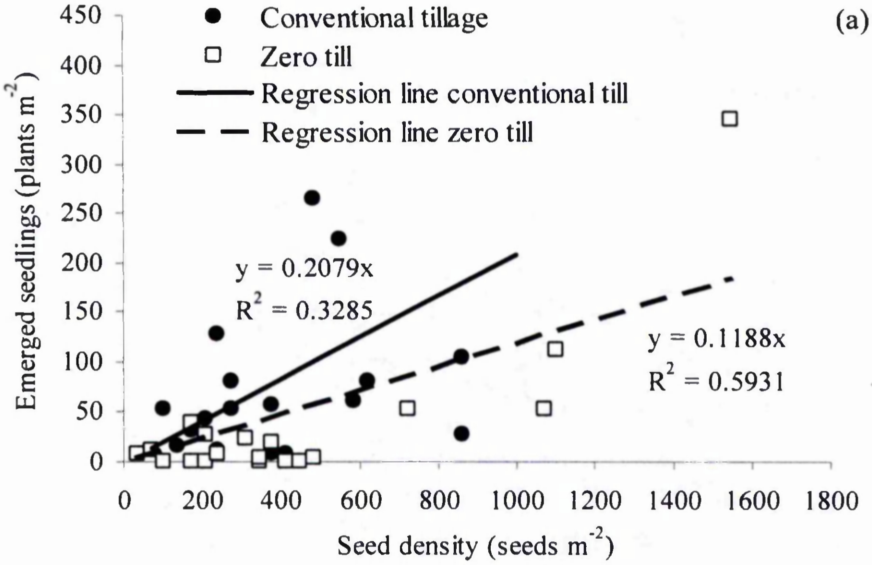
	Pirthala	*Narnaund*
First flush	0.003	0.003
Second flush	0.013	
Third flush	0.007	0.675

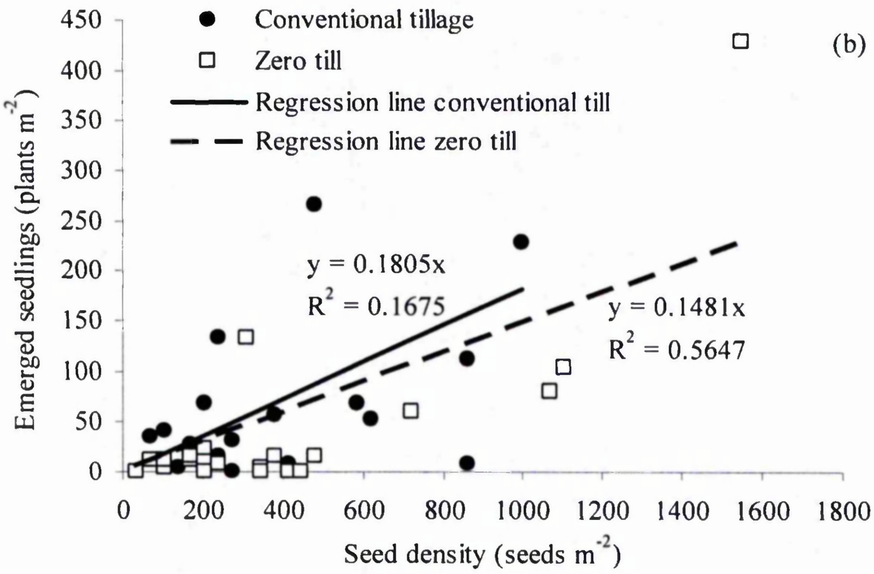
At Pirthala, no difference in relative vertical distribution of seeds through the soil profile between the two tillage systems was found. At Narnaund, the observed accumulation of seeds in the upper layers of the soil in fields under zero tillage would be expected to favour seedling emergence in these plots. However, seedling emergence rate in fields under conventional tillage was higher than in fields under zero tillage. Therefore, other factors apart from the relative vertical distribution of the seeds were likely to be involved in regulating the emergence rate. The reduced emergence rate in fields under zero tillage during the 1st flush of germination may be attributed to differences in moisture distribution through the soil profile. It was observed in the fields that conventional ploughing resulted in an equal distribution of the available moisture over the upper 10cm of the soil. The lack of cultivations in plots under zero tillage allowed a crust to develop on the soil surface, preventing seeds from the upper layer to germinate and mechanically impeding seedlings from the lower layers to emerge. It was also noticed in the field that most 1st flush seedlings in plots under zero tillage emerged within the row, where the crust was broken apart by the seed drill. In plots under conventional tillage, 1st flush seedlings were randomly scattered over the field.

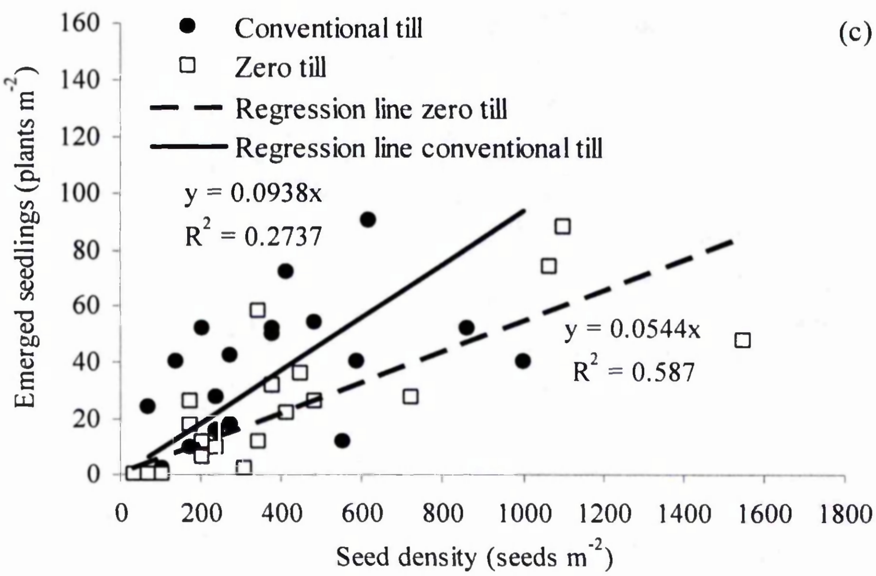
After first irrigation, the soil was thoroughly wetted and moisture conditions were expected to be similar in both tillage systems. However, also the emergence rates for 2nd flush and 3rd

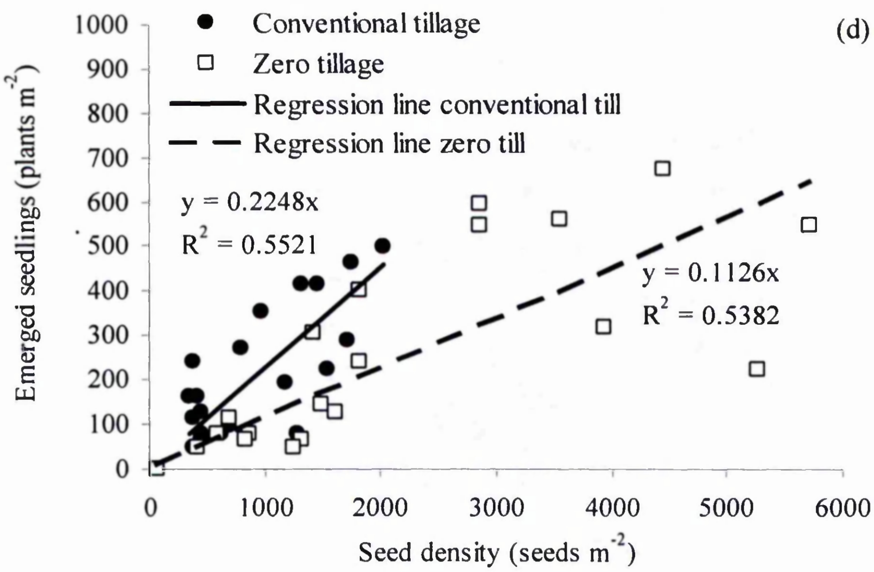
flush at Pirthala (post-irrigation) were slightly, though significantly reduced under zero tillage compared with conventional tillage. This indicated that other factors, such as differences in soil chemical and physical properties, soil temperature and the lack of mechanical or light stimulation to break seed dormancy during ploughing, may also be involved in regulating *P. minor* germination behaviour [Botto *et al.*, 1998].

Correlation coefficients between seedbank size and emerged seedling density varied between 0.17 and 0.59. The average correlation coefficient for zero tillage was higher than for conventional tillage (0.546 vs. 0.320), which suggests that the value of soil seedbank estimates for predicting seedling emergence is higher in fields under zero tillage than in fields under conventional tillage. Reduced soil disturbance in fields under zero tillage may diminish the environmental background noise, improving the accuracy of prediction. Correlation coefficients varying between 0.17 and 0.59 are comparable with those found in other published studies aiming to establish a relationship between seedbank size and emerged seedlings [Cardina & Sparrow, 1996]. Correlations of this strength are usually not sufficient to accurately predict weed seedling populations based on soil seed samples, indicating that other factors besides soil seedbank composition and tillage regime are involved in determining seedling emergence.


(a)
Conventional tillage
Zero till
Regression line conventional till
Regression line zero till
y = 0.2079x
R² = 0.3285
y = 0.1188x
R² = 0.5931
Emerged seedlings (plants m⁻²)
Seed density (seeds m⁻²)
0
50
100
150
200
250
300
350
400
450
0
200
400
600
800
1000
1200
1400
1600
1800


(b)
Conventional tillage
Zero till
Regression line conventional till
Regression line zero till
y = 0.1805x
R² = 0.1675
y = 0.1481x
R² = 0.5647
Emerged seedlings (plants m⁻²)
Seed density (seeds m⁻²)
0
50
100
150
200
250
300
350
400
450
0
200
400
600
800
1000
1200
1400
1600
1800


(c)
Conventional till
Zero till
Regression line zero till
Regression line conventional till
y = 0.0938x
R² = 0.2737
y = 0.0544x
R² = 0.587
Emerged seedlings (plants m⁻²)
Seed density (seeds m⁻²)
0
20
40
60
80
100
120
140
160
0
200
400
600
800
1000
1200
1400
1600
1800



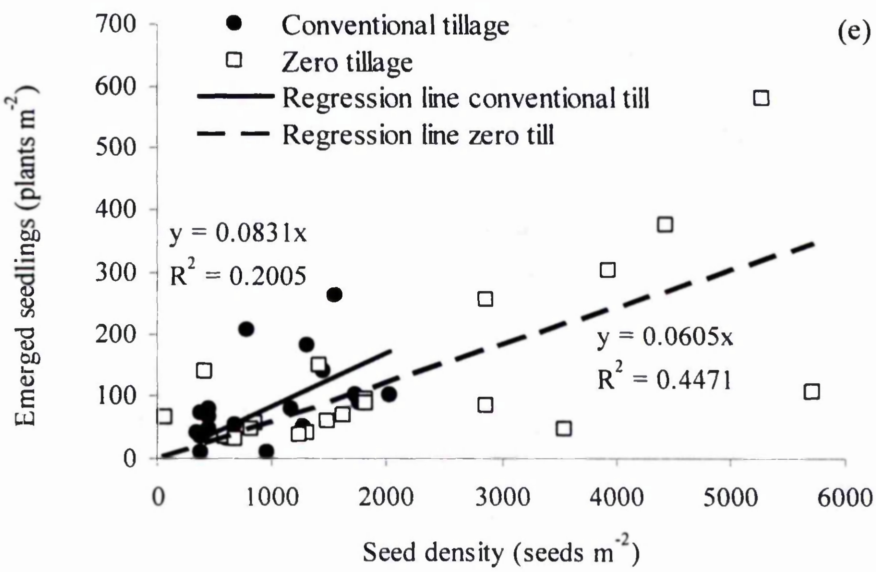


Figure 3.3 Relationships between soil seed density and emerged seedlings for *P. minor* in wheat, using simple linear regression techniques for:

(a) First flush of germination at Pirthala
(b) Second flush of germination at Pirthala (post irrigation)
(c) Third flush of germination at Pirthala (post herbicide application)
(d) First flush of germination at Narnaund
(e) Third flush of germination at Narnaund (post herbicide application)

3.3.3 Midseason harvest

At both locations, herbicide application influenced the density of 1st flush *P. minor* plants and, to a lesser extent, the density of 2nd flush plants [Table 3.3, Figure 3.4]. Plants belonging to the 3rd flush, emerging after herbicide application, were not affected by weed control treatments. The mortality rate of seedlings in IPU-treated fields equalled that of the control treatment at both locations [Table 3.4], suggesting that the *P. minor* biotypes were fully resistant to the applied dose of IPU. Negative mortality rates suggest an increase in plant density between seedling emergence and midseason for some treatments, but these values should be treated with caution as associated standard errors were high and negative mortality rates were not significantly different from zero. Fields treated with clodinafop and sulfosulfuron had fewer 1st flush plants at Narnaund than at Pirthala. This could be related with a better performance of herbicides at Narnaund, or with the delayed assessment date at Narnaund, allowing plants affected by herbicides more time to die.

Table 3.3 The effect of tillage regime and herbicides on *P. minor* density, *P. minor* plant biomass, total *P. minor* and wheat biomass at midseason (F_{pr} calculated by ANOVA).

	Pirthala		*Narnaund*	
	Tillage	*Herbicide*	*Tillage*	*Herbicide*
Density 1st flush	*0.037*	*0.013*	0.749	*0.002*
Density 2nd flush	0.317	*0.007*	0.988	0.192
Density 3rd flush	0.118	0.221	0.164	0.083
Mortality rate 1st flush	0.642	0.080	0.624	*0.012*
Mortality rate 2nd flush	0.834	*0.035*		
Plant biomass 1st flush			0.271	0.112
Plant biomass 2nd flush			0.509	0.215
Plant biomass 3rd flush			0.155	0.759
Total *P. minor* biomass	0.140	*<0.001*	0.895	*0.005*
Wheat biomass	*0.018*	*0.042*	0.687	*0.003*

The density of *P. minor* seeds in the soil and the number of emerged seedlings before spraying was higher at Narnaund than at Pirthala. Nevertheless, at midseason, the density of the 1st and 2nd flush in fields treated without herbicides or with IPU was equal at both locations. Consequently, the associated mortality rate was higher at Narnaund than at Pirthala. Self-thinning was likely to be responsible for the increased mortality in fields with high seedling density. These results suggest that the soil seedbank composition and seedling density is a relatively unimportant factor determining *P. minor* densities later in the season. However, this allegation may only be valid under the present conditions of relatively dense soil seedbanks. The density of 3rd flush plants was roughly three times higher at Narnaund than at Pirthala, reflecting the difference in soil seedbank composition. At the time of sampling, 3rd flush plants would not have been subject to self-thinning yet.

Table 3.4 *P. minor* mortality rate of 1st and 2nd flush seedlings after herbicide application at midseason (SE between parentheses)

	Pirthala		*Narnaund*
	1st flush	*2nd flush*	*1st flush*
Control	-0.17 (0.29)	0.24 (0.11)	0.83 (0.05)
Isoproturon	-0.11 (0.30)	0.34 (0.15)	0.68 (0.10)
Sulfosulfuron	0.59 (0.24)	0.97 (0.02)	0.99 (0.01)
Fenoxaprop	0.36 (0.30)	0.64 (0.15)	0.74 (0.13)
Clodinafop	0.85 (0.09)	0.90 (0.05)	1.00 (0.00)

The mortality rate of seedlings in fenoxaprop-treated plots at Narnaund equalled that of the control treatment. This field had no history of fenoxaprop usage. Therefore, if this poor control rate cannot be attributed to faulty herbicide application, the results provide a strong indication that the *P. minor* biotype in the field was cross-resistant against fenoxaprop. Seeds collected from fenoxaprop-sprayed fields at Narnaund have been collected and their resistance characteristics will be tested during the next growing season (2002-2003).

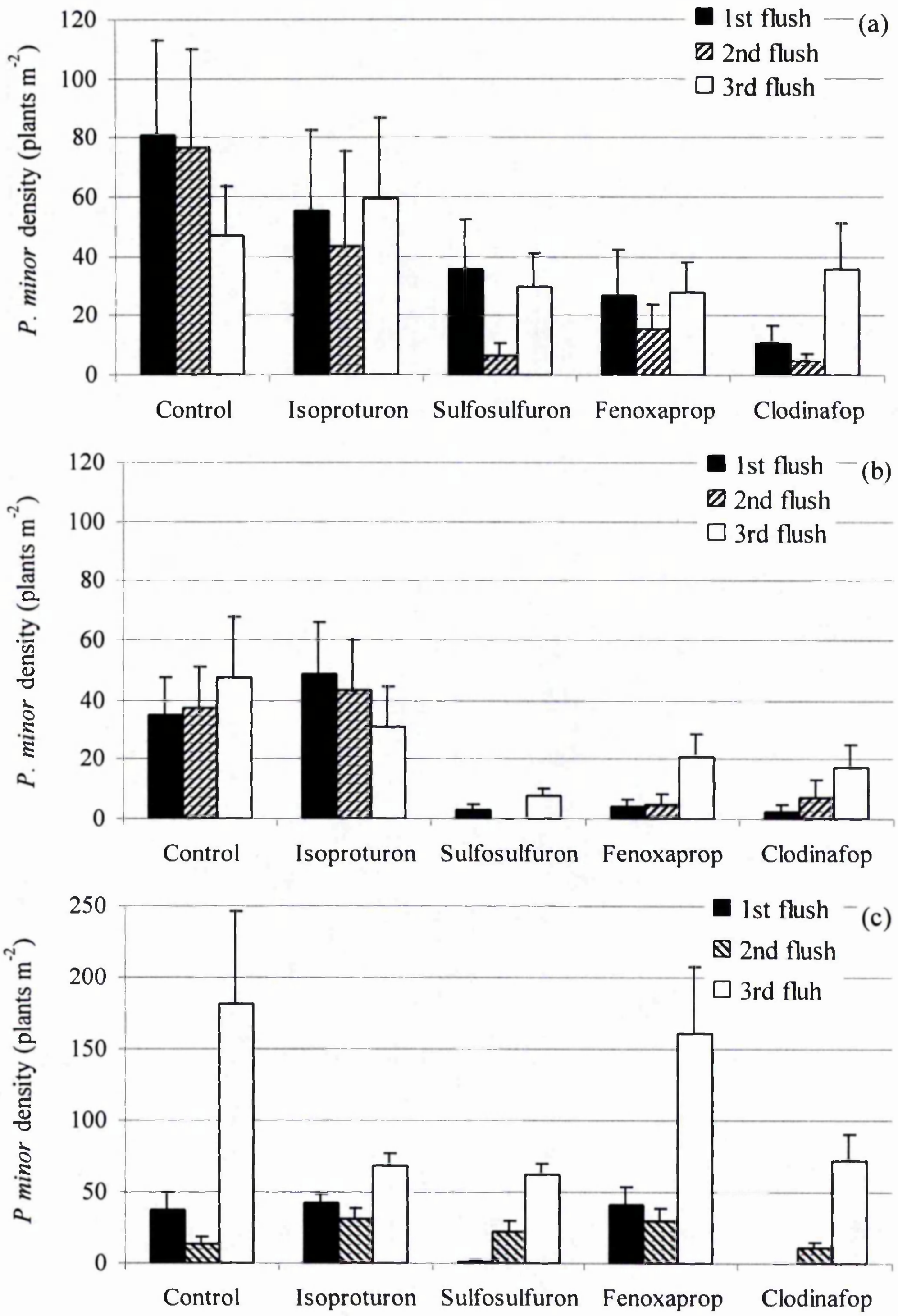


Figure 3.4 Effect of herbicides on *P. minor* densities of 1st, 2nd and 3rd flush at midseason for:

(a) Pirthala, conventional tillage
(b) Pirthala, zero tillage
(c) Narnaund, both tillage systems together

Plots under zero tillage had reduced densities of 1st flush *P. minor* plants and increased wheat biomass at Pirthala, in comparison with conventional tillage. [Table 3.3, Figure 3.4]. Since tillage regime did not affect the mortality rate of 1st or 2nd flush plants, the difference in plant density can probably be attributed to the reduced seedling emergence in zero-tilled fields earlier in the season. At Narnaund, 1st flush seedling densities early in the season were equal for both tillage systems. Consequently, there is no effect of tillage regime on *P. minor* densities at midseason harvest. In addition, the results confirm that the negative effect of zero tillage on *P. minor* population size is related to a reduced seedling emergence early in the growing season and not to an enhanced mortality rate or improved herbicide efficacy later in the season.

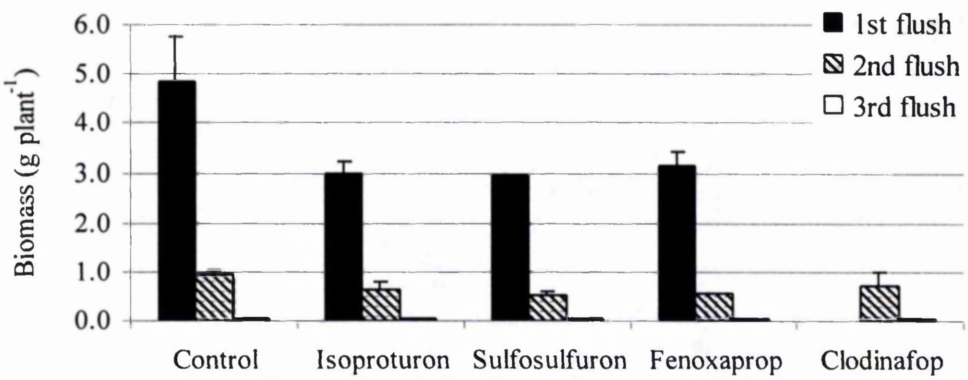


Figure 3.5 Effect of herbicides on individual *P. minor* plant weight at Narnaund at midseason. No 1st flush plants were harvested in fields treated with clodinafop.

Individual *P. minor* plant weight at Narnaund was 3.65g for the 1st flush, 0.67g for the 2nd flush and 0.028g for the 3rd flush [Figure 3.5]. Isoproturon, fenoxaprop and sulfosulfuron treatment reduced the biomass of the surviving plants compared with control by roughly 35%, but this difference was not significant [Table 3.3]. No 1st flush plants were found in fields treated with clodinafop. Herbicides affected *P. minor* densities rather than individual plant weight. Consequently, *P. minor* biomass on an area basis reflected the variation in 1st and 2nd flush plant densities, which contributed most to the total biomass [Figure 3.6]. High *P. minor* biomass coincided with reduced wheat biomass, indicating that weed competitive pressure was a major constraint for wheat biomass accumulation.

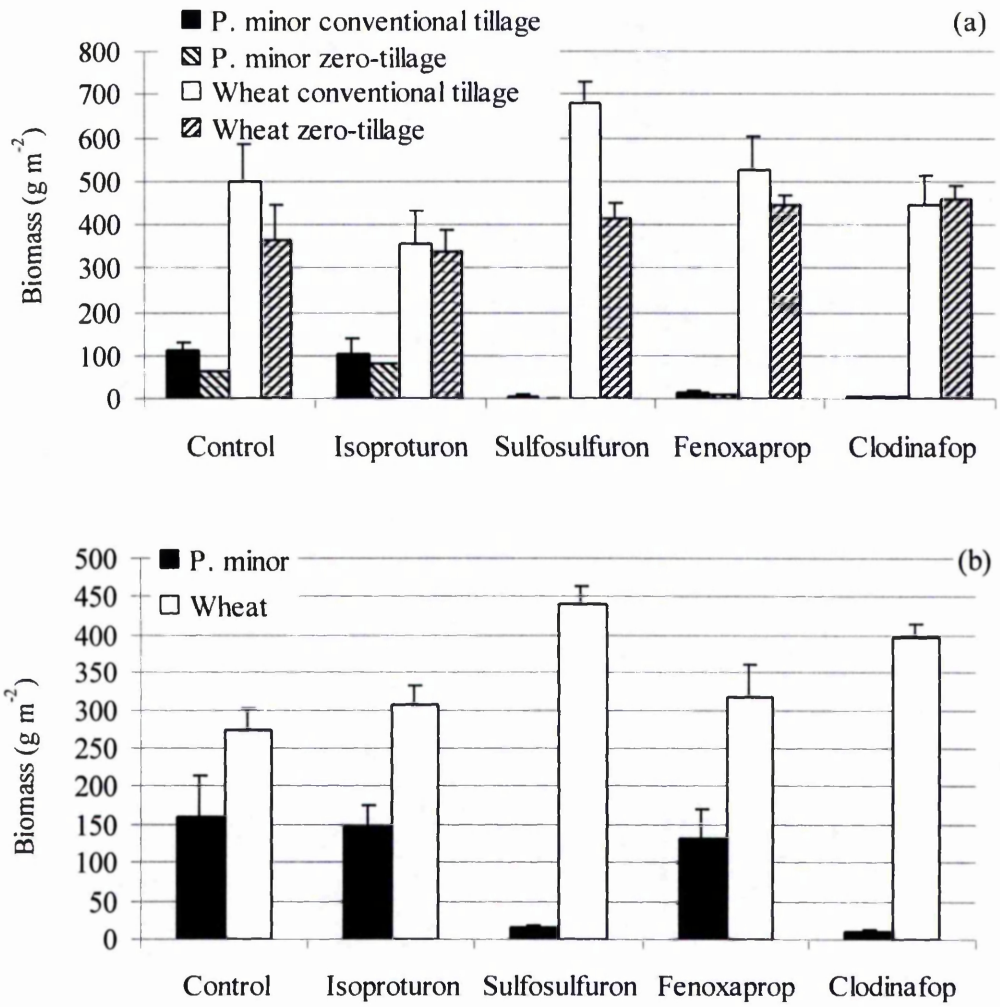


Figure 3.6 Effect of herbicides on *P. minor* and wheat biomass at midseason for:
(a) Pirthala, conventional and zero tillage separately
(b) Narnaund, both tillage systems together.

3.3.4 Final harvest

In line with the earlier assessments, *P. minor* densities and biomass were strongly affected by herbicide treatments, while effects of tillage regime on *P. minor* density and biomass were not detected [Figures 3.7&3.8; Table 3.5]. IPU and fenoxaprop gave poor weed control at both locations, suggesting that *P. minor* at Pirthala was also cross-resistant against fenoxaprop. Few *P. minor* plants survived treatment with clodinafop or sulfosulfuron at either location. Many 1st and 2nd flush plants that were still alive in fields treated with clodinafop or sulfosulfuron at Pirthala at midseason, failed to survive until final harvest. Individual *P. minor* plant weight was relatively stable among treatments [Table 3.6], as was observed at midseason, suggesting that plants surviving herbicide treatment were not severely limited in their ability to accumulate biomass. In Table 3.6, standard errors for means within herbicide treatments were relatively high, as plants from 1st, 2nd and 3rd flush plants varied in size, but were not distinguished during final harvest.

Table 3.5 Effect of tillage and weed control on *P. minor* density and biomass and wheat biomass and grain yield at final harvest (F_{pr} as calculated by ANOVA).

	Pirthala		*Narnaund*	
	Tillage	*Herbicide*	*Tillage*	*Herbicide*
P. minor density	0.460	*<0.001*	0.793	*0.003*
P. minor biomass	0.575	*<0.001*	0.354	*0.011*
Wheat biomass	0.794	*0.030*	0.299	*0.003*
Wheat grain yield	0.413	0.074	0.207	*0.034*

Table 3.6 *P. minor* plant biomass (g $plant^{-1}$) as affected by weed control treatments at final harvest (SE between parentheses).

	Pirthala	*Narnaund*
Control	4.56 (0.87)	4.92 (0.98)
Isoproturon	6.79 (2.70)	6.05 (1.11)
Sulfosulfuron	6.94 (0.84)	
Fenoxaprop	5.14 (1.13)	4.05 (0.52)
Clodinafop	3.50 (2.65)	4.96 (1.07)

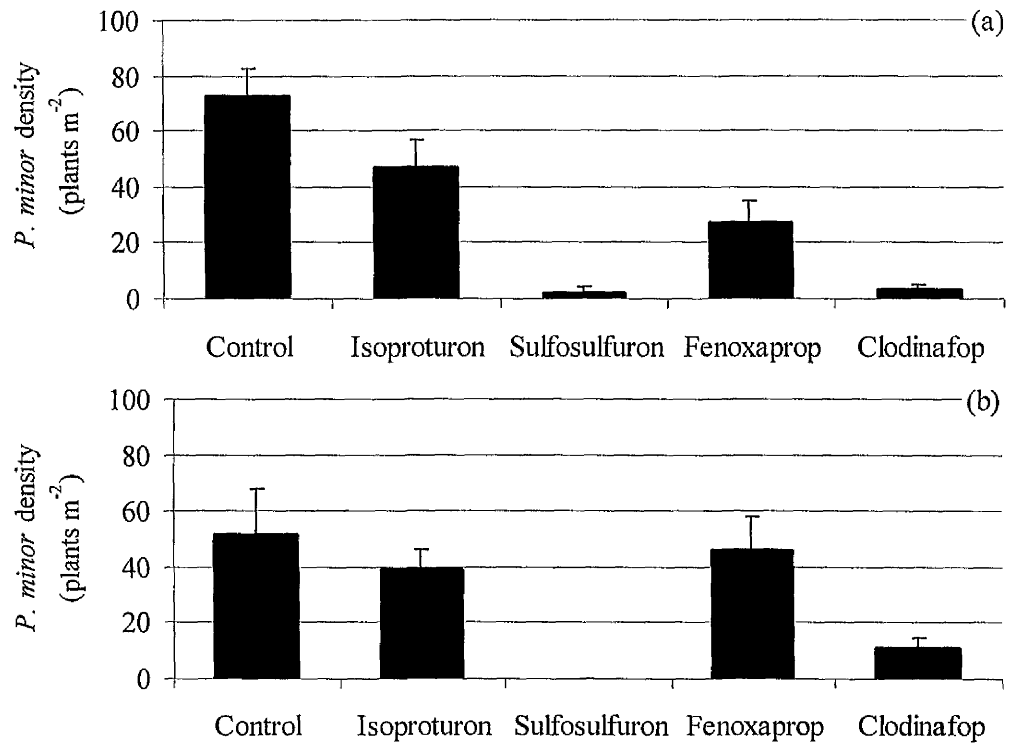


Figure 3.7 Effect of herbicides on *P. minor* densities for (a) Pirthala and (b) Narnaund at final harvest; data from both tillage systems were lumped together.

The contribution of the density of the three flushes as assessed at midseason, to the total density of *P. minor* plants at final harvest was estimated using multiple regression analysis [Table 3.7]. The regression coefficients can be regarded as estimates of the survival rate of each flush from midseason until final harvest. At Pirthala, the fraction of variance accounted for in the regression analysis was relatively low, while standard errors of the regression parameters were relatively high. This could be related with the suggestion made in Section 3.3.3 that plants lethally-affected by clodinafop and sulfosulfuron treatment were not dead yet when the density was assessed at midseason, reducing the value of midseason plant densities for predicting final plant density. At Narnaund on the other hand, a good correlation was found between midseason plant densities and final plant densities. Survival rate of the 1st flush was estimated 0.70, while survival rates of the 2nd and 3rd flush was estimated to be 0.03 and

0.10 respectively, which suggests that the 1st flush was most important in determining the final plant density, while only a small fraction of the 2nd and 3rd flush plants at midseason survived until final harvest. Plants belonging to the 1st flush emerge along with wheat, giving them a better position to compete with the crop than the 2nd flush plants emerging in December below the wheat canopy. Plants belonging to the 3rd flush, emerging late in the season, may experience slightly improved growing conditions at the end of the growing season when wheat leaves yellow and allow more light to reach the plants underneath the canopy. This may explain why the survival rate of 3rd flush plants is slightly higher than that of 2nd flush plants.

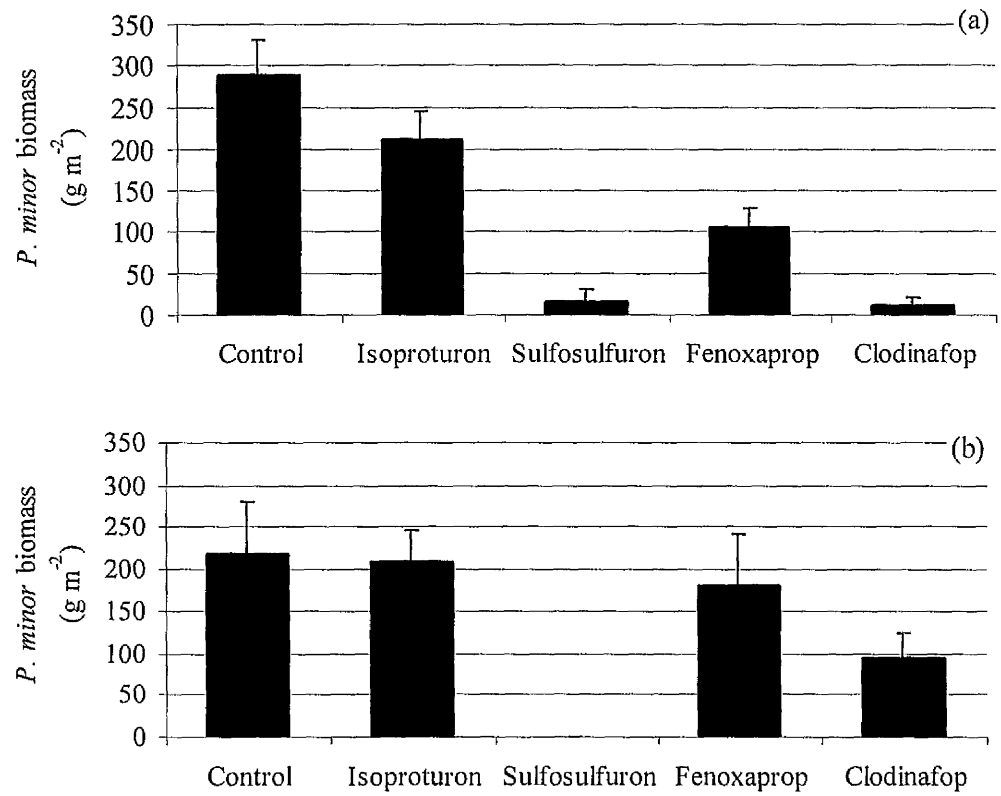


Figure 3.8 Effect of herbicides on *P. minor* biomass for (a) Pirthala and (b) Narnaund at final harvest; data from both tillage systems were lumped together.

Table 3.7 Contribution of various flushes at mid-season harvest to final *P. minor* density using multiple linear regression analysis (SE between parentheses).

	Pirthala *Regr. coeff.*	R^2	*Narnaund* *Regr. Coeff.*	R^2
1st flush	0.118 (0.178)	0.37	0.703 (0.105)	0.80
2nd flush	0.390 (0.206)		0.030 (0.123)	
3rd flush	0.376 (0.162)		0.103 (0.026)	

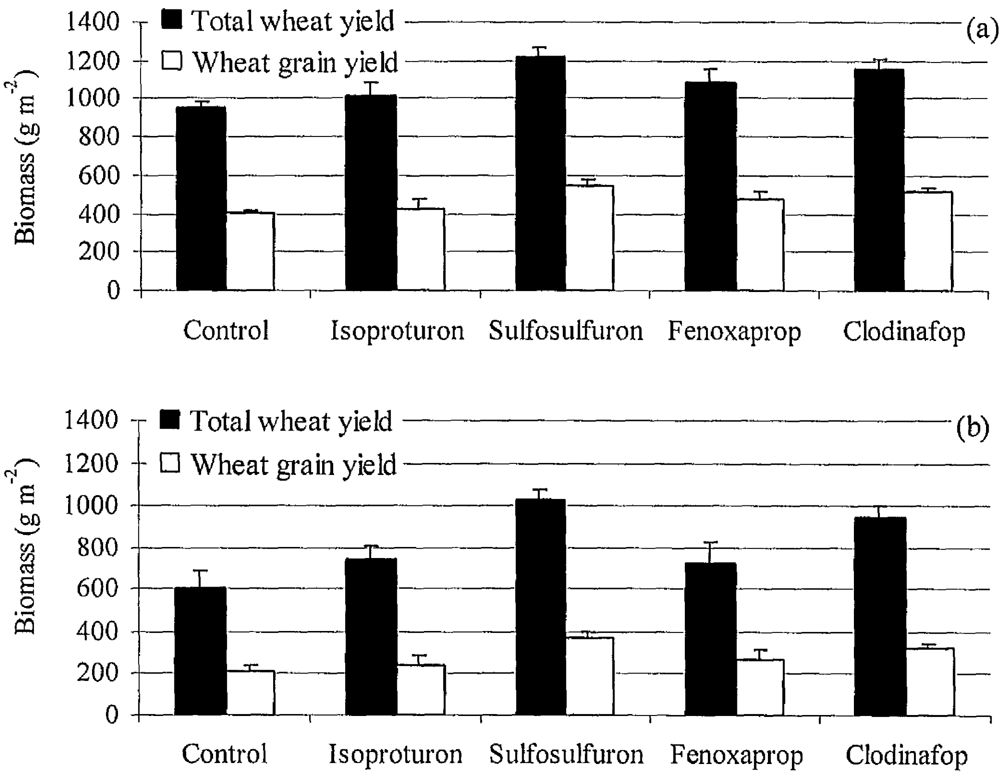


Figure 3.9 Effect of herbicides on total wheat and grain yield at final harvest for (a) Pirthala and (b) Narnaund.

Wheat biomass and grain yield were adversely affected by *P. minor* biomass, resulting in clear yield advantages for fields treated with clodinafop or sulfosulfuron [Figure 3.9]. Average harvest index was 0.42 and 0.36 at Pirthala and Narnaund, respectively. As wheat varieties, soil type and experimental treatments were equal at both locations, this difference in harvest index was likely to express variation in environmental factors. The low harvest index at Narnaund could have been caused by the relatively high day temperatures at the end of March 2002, resulting in accelerated plant maturation, early grain filling and a reduced harvest index.

The relationship between *P. minor* density and wheat yield loss was quantified using a rectangular hyperbola [Cousens, 1985a] [Table 3.8]. At Pirthala, the regression coefficient was low, indicating that other factors besides *P. minor* density determined the variance in wheat yield loss. The estimated value for the maximum wheat yield loss of 20% is probably unrealistic, as farmers have reported much higher yield losses due to *P. minor*. At Narnaund, the model accounted for a higher fraction of variance and estimates of model parameters may therefore be more reliable. However, a maximum wheat yield loss due to *P. minor* of 113% is obviously an overestimation. It is concluded that, even though wheat yield was clearly affected by weed control methods and *P. minor* densities, a large fraction of the variance in wheat yield could not be explained by variance in *P. minor* densities.

Table 3.8 Model parameters of a rectangular hyperbola relating *P. minor* density with wheat yield reduction (SE between parentheses).

	Pirthala	*Narnaund*
I	0.96 (1.92)	1.04 (0.68)
A	17.6 (2.8)	113 (45.4)
R^2	0.131	0.533

Models predicting wheat yield loss based on *P. minor* density may not be accurate because of *P. minor*'s germination behaviour and the phenotypic plasticity. *P. minor* seedlings germinate in distinguishable flushes and time of germination, as well as environmental conditions and weed control measures affect the plant's morphology and consequently, its competitive ability. A model based on relative leaf area may provide a more accurate prediction of wheat yield loss, as relative leaf area measured at a particular time reflects differences in both density and relative time of emergence of the weed [Kropff & Spitters, 1991; Kropff & Lotz, 1992]. Application of such models would require measurements of the leaf area of both wheat and *P. minor*.

3.3.5 Seed production

Strong evidence was found for a linear relationship between reproductive output and plant vegetative weight [Figure 3.10a]. This relationship varied little between Pirthala and Narnaund populations, suggesting that *P. minor* plants growing under Haryana conditions have a robust harvest index of around 0.27 and that the observed fecundity-plant size relationship may be valid for many sites. Also Thompson *et al.* [1991] and Wright [1993] reported linear relationships between reproductive and vegetative weight for several agricultural weeds and these relationships were often consistent from population to population within a species. The trendline's intercept with the x-axis in Figure 3.10a was 0.20 and the constant of the regression equation did not significantly differ from zero, indicating there is no effective threshold size for seed production. Also in the field it was observed that five-weeks old seedlings managed to produce seeds when triggered by environmental conditions. Thousand seed weight of *P. minor* varied between 1.2 and 2.2g and was only slightly affected by the vegetative weight of the mother plant [Figure 3.10b]. Small *P. minor* plants had reduced numbers of seeds rather than lower individual seed weights, which suggests that individual seed fitness may not be affected by size of the mother plant.

The germinability of seeds collected at Pirthala was tested after 8 months of storage under laboratory conditions at SAC. The germination rates of tested seed populations were 85-100% [Figure 3.11]. No relationship was found between weight of the mother plant or 1000-seed weight and germination rate in a simple linear regression test. This is in agreement with the suggestion made above that *P. minor* seed fitness is not determined by the size of the mother plant. However it may be possible to detect variation in seed fitness related to mother plant or seed weight only after a longer period of storage prior to testing.

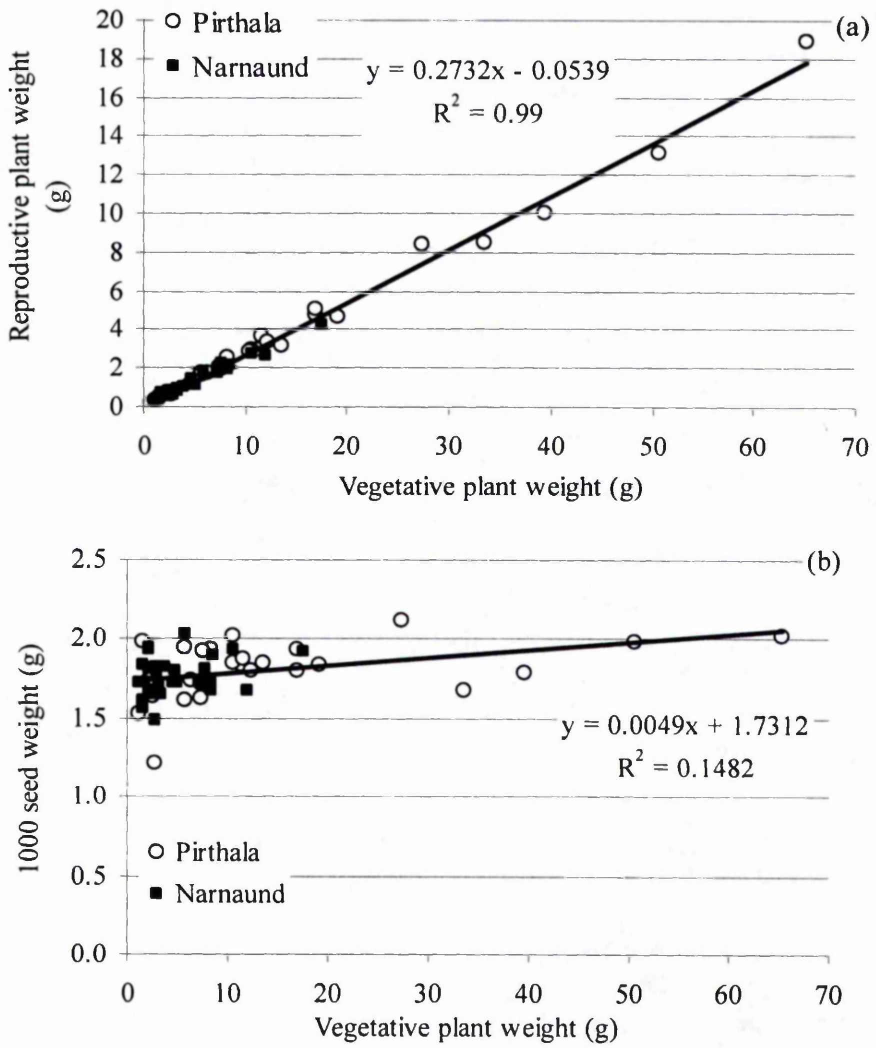


Figure 3.10 Relationship between *P. minor* vegetative weight and (a) reproductive output and (b) 1000 seed weight.

In the experimental fields, the average seed production was estimated to be 17096 seeds m^{-2}, and maximum seed production was 70281 seeds m^{-2}. After the most effective herbicide treatment (clodinafop), average *P. minor* biomass over both locations was 11.4g m^{-2} and estimated seed production was 6404 seeds m^{-2}. At the beginning of the growing season, average soil seedbank density was 1214 seeds m^{-2}. Thus, calculated seed return after clodinafop application exceeded the size of the seedbank at the beginning of the growing season by several times, suggesting an increase in seedling emergence in the subsequent year. In practise however, seedling density generally decreases in a year following the use of clodinafop. It is likely that a large proportion of the newly shed seeds fail to survive the summer. Such high seed mortality is common among weeds and may be caused by factors such as predation of seeds on the soil surface, straw burning and seed removal during wheat harvest. For *P. minor*, the fraction of unshed seeds on the mother plant removed from the field during wheat harvest may be high.

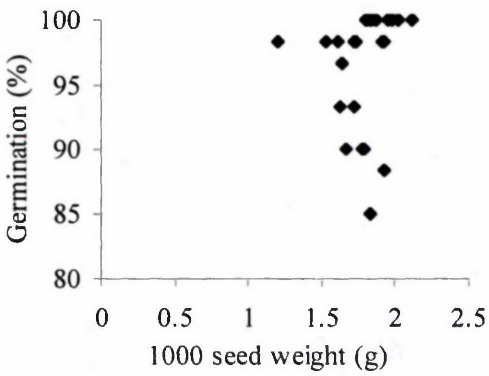


Figure 3.11 Relationship between *P. minor* seed weight and germinability after 8 months of storage under laboratory conditions. No correlation between seed weight and germinability was observed.

CHAPTER 4: A POPULATION DENSITY MODEL

4.1 Introduction

This chapter discusses the construction, calibration, validation and performance of a simulation model of the lifecycle of *P. minor* in competition in wheat. Plant population models may be divided into two groups [Cousens & Mortimer, 1995]. One group consists of single stage models, which only consider the density of a population at intervals of a single generation. These models make no assumption of what goes on within each generation and are purely descriptive. The other group is the multi-stage models, which divide the lifecycle of a species into a number of discrete stages and consider gains and losses from one stage to the next. These models may provide a higher level of mechanistic understanding of the processes regulating plant population size. Multi-stage models, in turn, can be divided into two categories. Single-cohort are models which assume that all plants emerge approximately at the same time and reach each development stage together in a single cohort. Multi-cohort models assume a population of multiple cohorts with different development stages and different germination, competitive and reproductive behaviour. Since *P. minor* germinates in clearly distinguishable flushes with different growth and reproduction characteristics, a multi-stage multi-cohort model was considered most appropriate to describe the lifecycle of *P. minor*.

Certain characteristics of the rice-wheat system assist the development of a weed population model. Weather conditions in Haryana during the wheat season are relatively stable and soil moisture conditions are largely dependent on farmers' irrigation management. Wheat requires irrigations at fixed intervals. *P. minor* can only germinate directly after irrigation when soil moisture conditions are high. *P. minor* germination behaviour is therefore regulated by farmers' decisions when to irrigate and the weed germinates in clearly distinguishable flushes, directly after each irrigation. Population models of other weed species often entail the simplification that the emergence date in the model is fixed, while in reality, weeds germinate in a period varying between several weeks up to several months and the germination rate is affected by many environmental conditions. With a population model of *P. minor*, showing fixed, short periods of emergence in the field, variance related to time of emergence can largely be avoided. In addition, most weed population models only deal with one weed species, while in reality several species determine the outcome of the crop-weed interaction. In Haryana, *P. minor* is the most widely abundant weed species in wheat and generally, no weed species besides *P. minor* play a role of significance in the crop-weed interaction.

The present model of the population dynamics of *P. minor* was developed with the objectives:

(i) to organise and summarise the existing knowledge of the lifecycle of *P. minor*;

(ii) to predict long-term effects of various weed control strategies;

(iii) to identify future research and extension priorities for *P. minor* control.

The model aimed to make optimal use of the limited information available on *P. minor* demography and the model's structure was adapted to the quality of the input data. This resulted in a hybrid mechanistic-empirical model. Many published multi-stage models of weed population dynamics reduce a weed's lifecycle to four stages: seeds in the soil, seedlings, adult plants and newly produced seeds on the mother plant [Colbach & Debaeke, 1998; Section 1.4.2]. Besides these four stages, the present model recognised a fifth stage: plant density at midseason after herbicide application. This allowed parametrisation of the model with data provided by the lifecycle studies described in Chapter 3. The main factors externally regulating the population size were tillage regime and herbicides. In the model, tillage regime affected population dynamics by regulating the seedling emergence rate and the relative distribution of seeds throughout the soil profile, which indirectly affected the density of emerged seedlings. Herbicide application regulated the survival rate of emerged seedlings until midseason and the survival rate of plants at midseason until final harvest.

4.2 Model design

4.2.1 Fortran Simulation Translator

The present model has been programmed in FORTRAN 77, using a simulation shell called Fortran Simulation Translator (FST) (Windows version 1.06, 2001 Wageningen Software Labs, Alterra). The Fortran Simulation Translator translates an FST program into FORTRAN subroutines with data files containing timer variables, model parameters and rerun specifications. The FST program contains the main model consisting of the dynamic model structure, a framework for the major process-related routines, a collection of utility routines which perform tasks, such as reading of parameter values from data files and generating model outputs, and the control structure for rerun facilities (Kraalingen, 1993). The dynamic loop of the main model cannot handle non-continuous structures, such as IF-THEN-ELSE structures, which are therefore placed outside the main program in subroutines using native FORTRAN statements.

FST distinguishes state variables, which are variables that are present continuously and represent a quantity of something. Changes in the value of state variables are regulated by rate equations. The solutions of rate equations are obtained by numerical integration using the Euler or rectangular integration method. Usually the rectangular integration method calculates the value of state variables with slight deviations from its associated analytical solutions, because the rectangular integration method assumes fixed rates of change for specific time intervals, while in reality, rate variables change continuously. However, the present model describes the lifecycle as a series of discrete steps from one generation to the next using difference equations to calculate the value of state variables in the following year. This is more appropriate to annual plants than the use of differential equations, which suggest that rate variables change continuously over time. If the time step of the model equals the time required to fulfil one lifecycle (one year for *P. minor*), the rectangular integration method produces the same outcomes as an analytical model would have done. Given the complexity of some of the equations and the presence of several time-dependent functions in the model, analytical solutions for the equations used in the model were impossible.

4.2.2 Model construction

The model described the lifecycle of *P. minor* using five main stages: (1) seeds in the soil, (2) emerged seedlings, (3) plant density at midseason (after herbicide application), (4) adult plant density and (5) seeds on mother plants [Figure 4.1]. The main processes externally regulating the population size were herbicide use and tillage regime. Wheat density was not explicitly included in the model, as no wheat-*P. minor* replacement studies have been reported and competition effects of wheat on *P. minor* have not been estimated. *P. minor* population size was intrinsically regulated by factors such as seed longevity, germination and emergence rate, self-thinning and seed production. The model contained a subroutine assigning values to parameters representing herbicide efficacy and plant survival later in the season, according to an input parameter expressing the type of weed control.

Three flushes of emergence were distinguished in the model: a 1st flush emerging along with the wheat, a 2nd flush emerging after the first irrigation, before herbicide application and a 3rd flush emerging after the second irrigation, after herbicide application. As equations calculating population size were often similar for the three flushes, array-variables were used in the simulation program to avoid lengthy repetitions of calculations. Array-variables contain a series of values representing a number of closely related variables, for example the number of emerged seedlings of the 1st, 2nd and 3rd flush. FST automatically repeats calculations of array-variables within a time loop as frequently as required to assign values to every single variable of the array-variable. The size of the array-variable is defined at the beginning of the simulation program, and in the present model, the size of all array variables equalled the number of flushes of emergence (3).

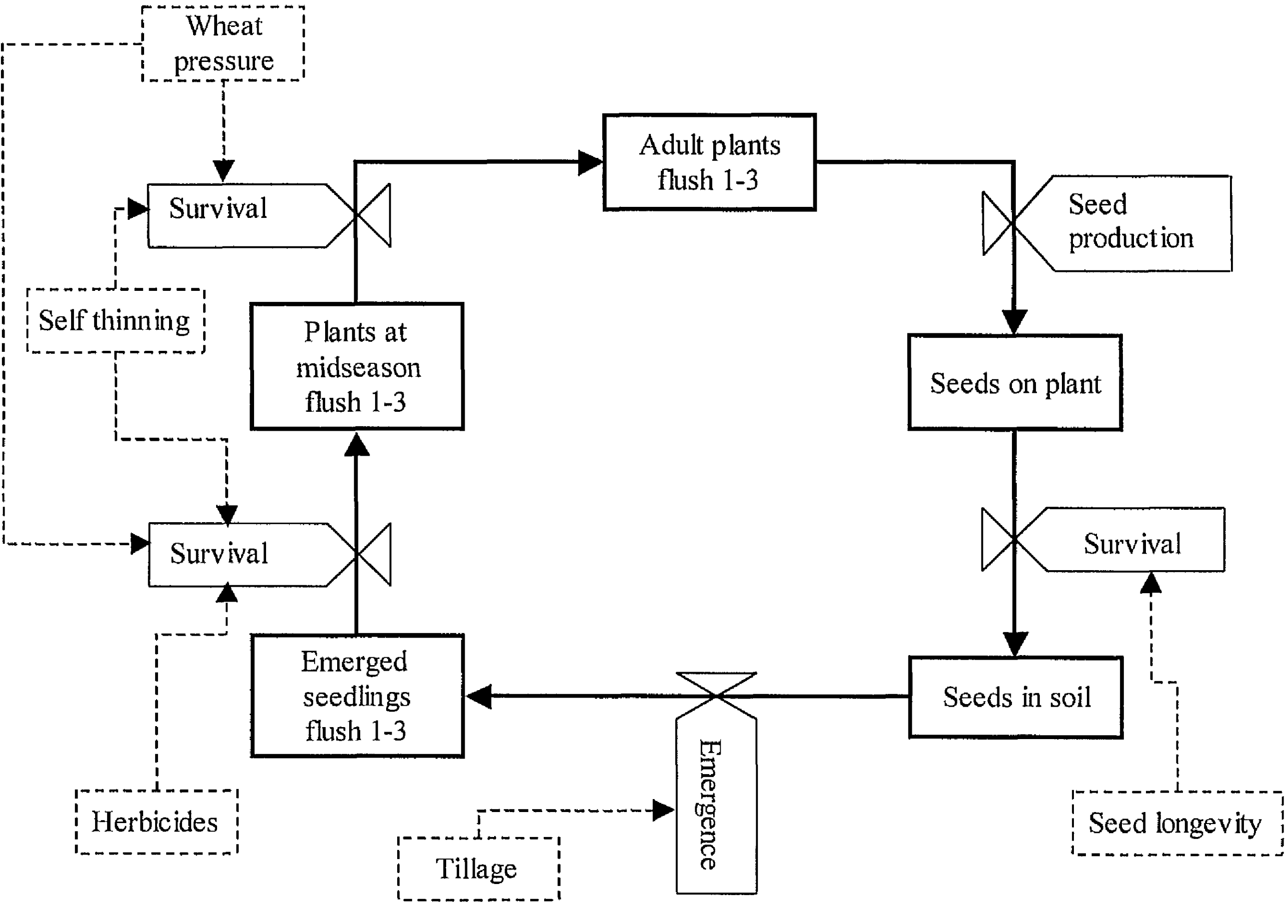


Figure 4.1 Flowchart illustrating the lifecycle of *Phalaris minor* in the the Indian rice-wheat rotation. Drawn lines indicate the lifecycle, broken lines indicate processes influencing the flow.

A step-by-step description of the construction of the model is given here. Appendix II contains a complete listing of the model in FST, definitions of the abbreviations used in the model can be found in Appendix III.

1. Soil seedbank

The seedbank is the only life stage in the model, which is present throughout the entire year. Unlike other life stages, the state of the soil seedbank directly depends on its state in the previous year, as seeds in the soil that do not emerge or decompose in one year are transferred to the next year. Soil seed density was therefore the only state variable in the simulation model. Soil seedbank size was regulated by the inflow of seeds through seed production and the outflow of seeds through emergence and mortality.

$NSS_{t+1} = NSS_t + NSSR_t$

$NSSR_t = SPROD_t - NEST_t - MORT_t$

t	time [y]
NSS	Total number of seeds in the soil [seeds m^{-2}]
$NSSR$	Change in seed density of the entire soil seedbank [seeds m^{-2}]
$SPROD$	Replenishment of the seedbank by newly produced seeds [seeds m^{-2}]
$NEST$	Total number of emerged seedlings [seedlings m^{-2}]
$MORT$	Number of seeds that die or germinate and fail to emerge [seeds m^{-2}]

Those seeds that failed to emerge were susceptible to decomposition and predation. Seed decline is usually exponential over time and occurs at a roughly constant rate. Therefore, yearly seed mortality was modelled as a function of a constant seed mortality rate and the number of seeds in the soil after emergence:

$MORT_t = MORTR \cdot (NSS_t - NEST_t)$

$MORTR$	Yearly mortality rate of seeds

2. Seedling emergence

The seedbank was separated into the soil layers 0-10cm and 10-20cm and the relative distribution of seeds over the two layers depended on tillage regime. Seed emergence was calculated as a linear function of seeds in the upper 10cm of the soil. Seeds buried below 10cm that did not decompose in one year could move to the upper layer and produce seedlings in the following year. Three flushes of emergence were distinguished and the emergence rate of each flush depended on tillage system.

$NSSA_t = NSS_t \cdot (1. - FSB_c)$

$NES_{t,k} = EMR_{c,k} \cdot NSSA_t$

$$NEST_t = \sum_{k=1}^{3} NES_{t,k}$$

c	Tillage system (conventional or zero tillage)
k	Flush ($k = 1 \ldots 3$)
NSSA	Number of seeds in the upper 10cm of the soil [seeds m^{-2}]
FSB_c	Fraction of seeds of the total seedbank below 10cm depth for tillage system *c*
NES_k	Number of emerged seedlings for flush *k* [seedlings m^{-2}]
$EMR_{c,k}$	Emergence rate of seedlings for tillage system *c*, flush *k* [seedlings $seed^{-1}$]

3. Midseason plant density

At midseason, herbicide spraying and interplant competition had reduced the density of 1st and 2nd flush plants. Plants belonging to the 3rd flush, emerged after herbicide spraying and were unaffected by herbicides and interplant competition at this stage. It was observed in the lifecycle studies [Chapter 3] that accumulative 1st and 2nd flush plant density never exceeded 150 plants m^{-2} at midseason, also in those treatments with high seedling densities earlier in the season, without the application of effective herbicides. Hence, density-induced mortality was likely to play an important role here.

In general, *P. minor* plants compete with wheat and with other *P. minor* plants belonging to the 1st and 2nd flush. Wheat density was assumed to be constant and was not explicitly included in the model. *P. minor* plants from the 1st and 2nd flush differ in size and should be modelled as two species competing with each other. However, the data from the field experiment did not provide sufficient information on the interaction between 1st and 2nd flush plants under herbicide-free conditions. Therefore, a simpler approach was chosen to model density-dependent mortality among first and second flush plants, using a rectangular hyperbola. The number of surviving plants of a particular flush was determined by the actual density of both flushes and the maximum number of plants of both flushes together, assuming that both flushes are equally competitive.

The general equation of a rectangular hyperbola is:

$$y(x) = A + \frac{B}{1 + D \cdot x} \tag{4.1}$$

Parameter y is the plant density of a particular flush at midseason, x is the plant density of a particular flush before interplant competition. The hyperbola was constrained in the origin, as the plant density at midseason is zero when the density of plants after spraying is zero:

$$A + B = 0 \Rightarrow y(x) = A - \frac{A}{1 + D \cdot x} \tag{4.2}$$

In addition, the slope of the curve when x → 0 equals 1, as no density-induced mortality occurs when plant densities are very low:

$$y'(x) = \frac{A \cdot D}{(1 + D \cdot x)^2} \tag{4.3}$$

$$y'(0) = 1 \Leftrightarrow 1 = \frac{A \cdot D}{1^2} \tag{4.4}$$

$$D = A^{-1} \tag{4.5}$$

Combining equation 4.2 and 4.5 gives:

$$y(x) = A - \frac{A}{1 + \frac{x}{A}} \tag{4.6}$$

Equation 4.6 can be simplified:

$$y(x) \cdot \left(1 + \frac{x}{A}\right) = A \cdot \left(1 + \frac{x}{A}\right) - A = x \tag{4.7}$$

$$y(x) = x \cdot \left(1 + \frac{x}{A}\right)^{-1} \tag{4.8}$$

The model assumed that interplant competition occurs after herbicide application. The density of plants after herbicide application, x, was modelled as a linear function of seedling density and herbicide efficiency rate $(NES \cdot (1 - HEFF))$.

Factor $\left(1 + \frac{x}{A}\right)$ in Equation 4.8 determines the relative reduction in plant density of a particular flush due to competitive pressure. As competitive pressure depends on the density of both flushes, x in factor $\left(1+\frac{x}{A}\right)$ represents the accumulative plant density before competition of both flushes. Parameter A expresses the maximum number of 1st and 2nd flush plants at midseason. Plant density at midseason was thus calculated as:

$$MID_{t,k} = NES_{t,k} \cdot \left(1 - HEFF_{h,k}\right) \cdot \left[1 + \frac{\sum_{k=1}^{2}\left(NES_{t,k} \cdot \left(1 - HEFF_{h,k}\right)\right)}{MIDMAX}\right]^{-1} \qquad \text{for } k = 1,2$$

$$MID_{t,k} = NES_{t,k} \qquad \text{for } k = 3$$

MID_k	Plant density at midseason for flush k [plants m^{-2}]
h	Herbicide type (no herbicides, isoproturon or clodinafop)
$HEFF_{h,k}$	Efficacy of herbicide h for controlling flush k [plants $seedling^{-1}$]
$MIDMAX$	Maximum plant density at midseason of 1st and 2nd flush together [plants m^{-2}]

4. Adult plant density

Experimental data suggested that the survival rate of the three flushes from midseason until final harvest is a rather stable parameter unaffected by plant density. The number of adult plants was thus calculated as a linear function of plant density at midseason and the survival rate from midseason until final harvest:

$$APD_{t,k} = SURV_{h,k} \cdot MID_{t,k}$$

APD_k	Adult plant density for flush k [plants m^{-2}]
$SURV_{h,k}$	Survival rate of plants from midseason until final harvest after application of herbicide h for flush k [plants $plant^{-1}$]

Total plant biomass at final harvest was a function of plant density and biomass of each flush:

$$TBIOM_t = \sum_{k=1}^{3}\left(APD_{t,k} \cdot BIOM_{t,k}\right)$$

$TBIOM$	Total biomass of adult plants [g m^{-2}]

$BIOM_k$ Individual plant weight for flush k [g plant^{-1}]

5. Seed production

A strong correlation between *P. minor* vegetative weight and reproductive weight was observed in Section 3.3.5. Seed weight on an area basis was thus modelled as a function of total plant biomass and the harvest index. After dividing seed weight on an area basis by the weight of an individual seed, seed production on an area basis was obtained:

$$SPROD_t = \frac{TBIOM_t \cdot HI}{SEEDW}$$

SPROD Seed production [seeds m^{-2}]

HI Harvest index [g g^{-1}]

SEEDW Weight of an individual seed [g seed^{-1}]

After adding freshly shed seeds to the soil seed bank, the lifecycle was completed.

4.2.3 Parameterisation

The model was parameterised using data from field studies presented in Chapter 2 and 3. It was also necessary to specify the initial seedbank size, but the choice of initial seed density is rather arbitrarily. The following values were assigned to the model's input parameters:

1. Soil seedbank parameters

NSSI = 2000.

Number of seeds in the soil [seeds m^{-2}] at $t = 0$

$FSBZ = 0.125^{a}$; $FSBC = 0.23^{b}$

Fraction of seeds in the soil buried below 10cm for zero tillage[a] and conventional tillage[b].

2. Seedling emergence parameters

$EMRZ_{k=1...3} = (0.12, 0.15, 0.06)^{a}$

$EMRC_{k=1...3} = (0.22, 0.18, 0.09)^{b}$

Emergence rates of 1st, 2nd and 3rd flush for zero tillage[a] and conventional tillage[b].

3. Midseason plant density parameters

MIDMAX = 300.

Maximum plant density at midseason of 1st and 2nd flush together [plants m^{-2}].

$HEFF_{k=1,2} = (0.0, 0.0)$ [a]

$HEFF_{k=1,2} = (0.3, 0.3)$ [b]

$HEFF_{k=1,2} = (0.98, 0.95)$ [c]

Control efficacy of 1st and 2nd flush *P. minor* after application of no herbicides[a], isoproturon[b] or clodinafop[c].

4. Adult plant density parameters

$BIOMP_{k=1...3} = (5.14, 3.72, 2.29)$

Plant biomass for 1st, 2nd and 3rd flush [g $plant^{-1}$].

$SURV_{k=1...3} = (0.617, 0.223, 0.131)$[a]

$SURV_{k=1...3} = (0.617, 0.223, 0.131)$[b]

$SURV_{k=1...3} = (0.693, 0.077, 0.059)$[c]

Survival rate for 1st, 2nd and 3rd flush plant from midseason until final harvest after application of no herbicides[a], isoproturon[b] or clodinafop[c].

5. Seed production parameters

HI = 0.273

Harvest Index [g g^{-1}]

SEEDW = 0.00178

Seed weight [g $seed^{-1}$]

4.3 Model calibration, validation and sensitivity analysis

4.3.1 Calibration

The first simulation, using weed control rates achieved by clodinafop in practice, showed a sigmoid increase in *P. minor* densities, which stabilised between 2000-3000 plants m^{-2} [Figure 4.2]; this is far above the maximum *P. minor* densities observed in the field. Closer examination of the simulation data revealed that, in the first year, final plant densities varied between 11 and 15 plants m^{-2}, mostly consisting of 3^{rd} flush plants. Such densities are common in the field after clodinafop application, suggesting that processes of herbicide-induced and density-dependent mortality were correctly simulated. Subsequent seed production varied between 5000 and 8000 seeds m^{-2}, which also in line with field data. In the model, the soil seedbank density drastically increased after first seed shed and, during the second year, seedling and adult plant density increased accordingly. 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. Given that adult plant populations and seed production were correctly simulated, a possible reason for the lack of fit between the model and field observations is that large losses occur between seed production and soil seedbank density at the beginning of the following growing season. This endemic control may be very important in regulating the population size, as suggested before in Section 3.3.5.

To enable further simulations, a seed survival parameter (*SSURV*) was included to calibrate the model. Survey data [Chapter 5] suggested that after application of clodinafop, *P. minor* adult plant densities decrease in the subsequent year by 20-50%. To obtain such decrease in population density, the seed survival parameter should vary between 0.15 and 0.25 [Figure 4.3]. The survival parameter was set at 0.2, assuming that 80% of the recently shed seeds fail to survive until the beginning of the subsequent growing season.

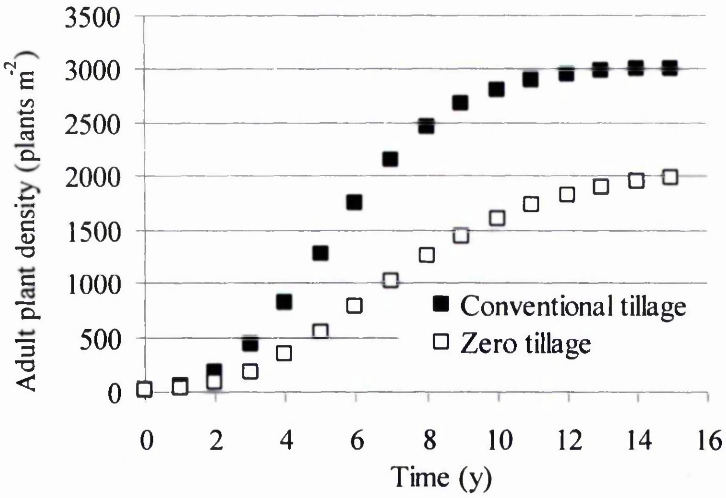


Figure 4.2 Simulated *P. minor* demography with continuous use of clodinafop, before calibration. Adult plant densities of 2000-3000 plants m^{-2} have never been observed in the fields.

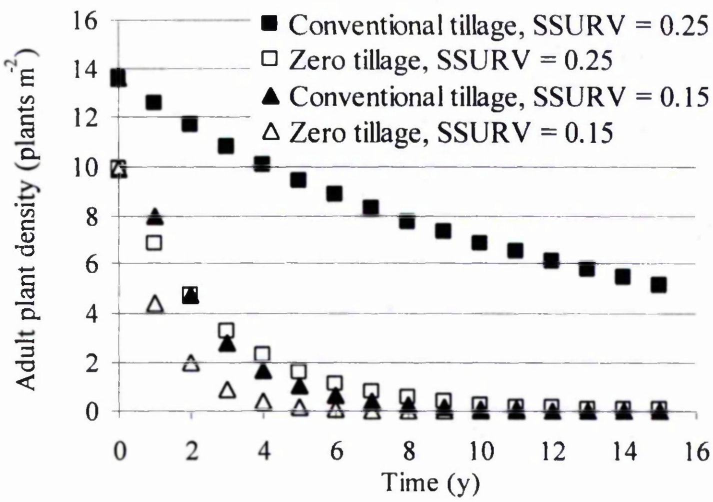


Figure 4.3 Effect of the seed survival parameter (SSURV) on simulated *P. minor* demography.

4.3.2 Validation

To validate the model, simulated outputs were compared with results from two independent studies on the long-term effects of conventional and zero tillage on *P. minor* seedling emergence in Karnal district [Singh *et al.*, 2002b] and Fatehabad / Kaithal district [Yadav *et al.*, 2002b] in Haryana. The experimental fields were treated with clodinafop or with

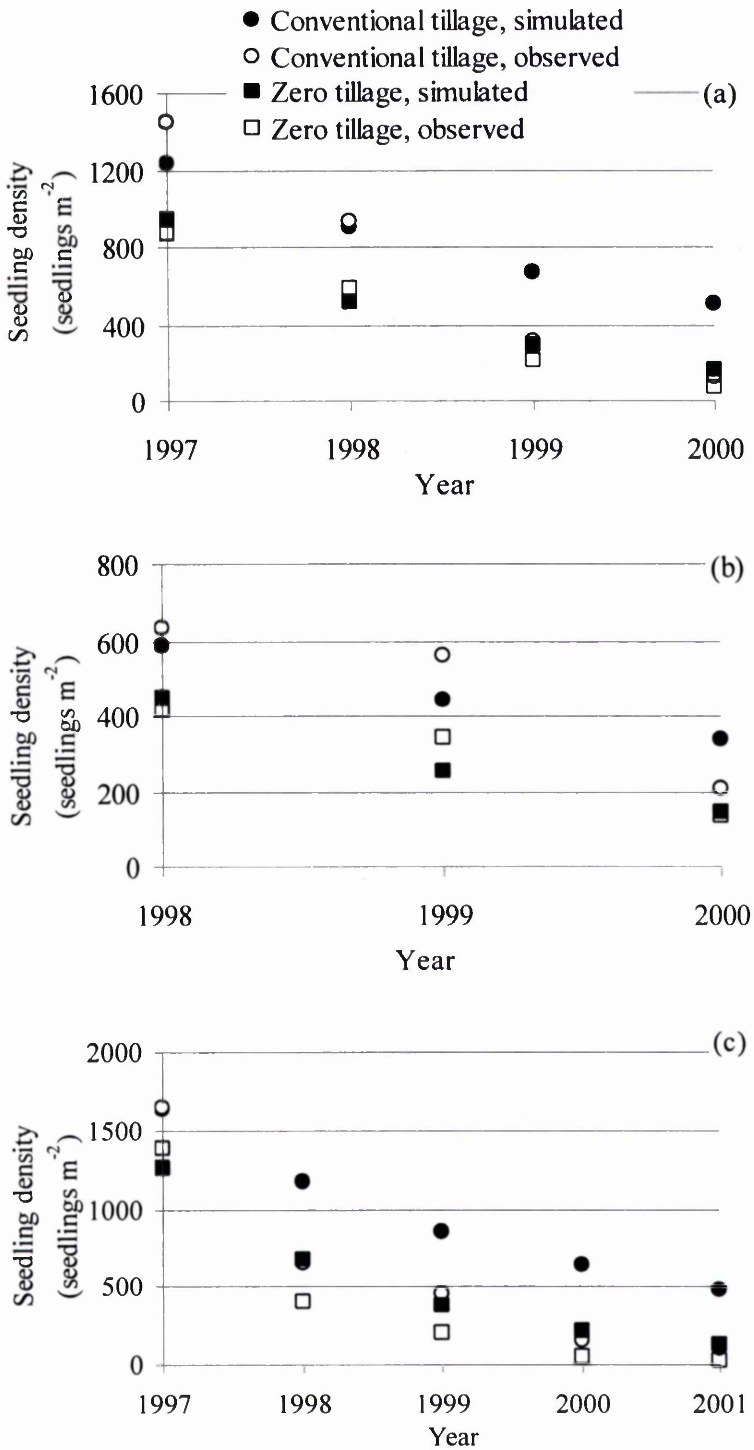


Figure 4.4 Validation of *P.minor* population model for various locations within Haryana:
(a) Karnal, 1 site [Singh *et al.*, 2002b]
(b) Karnal, 1 site [Singh *et al.*, 2002b]
(c) Fatehabad, average of 5 sites [Yadav *et al.*, 2002b]

sulfosulfuron, which are both highly effective in controlling *P. minor*. Seedling density of 1st and 2nd flush was assessed in the fields, 35 DAS (before herbicide application). Initial seedling density in the model was adjusted for each site to obtain the observed seedling density in the first year of simulation. The initial soil seedbank density (*NSSI*) was set at 4000, 1900 and 5300 for Studies a, b & c respectively [Figure 4.4]. Simulated seedling dynamics in zero tillage systems closely matched the observed field data. In conventional tillage systems, the model correctly simulated the qualitative behaviour of the field populations, but underestimated the relative reduction in *P. minor* population after application of clodinafop or sulfosulfuron in Figure 4.4a & c.

4.3.3 Sensitivity analysis

In the model, all parameters were assumed to be constants. In reality however, many parameters vary between years and locations. Therefore, a sensitivity coefficient was calculated for input parameters which were likely to vary in the field by reducing the value of these input parameters by 10, 20 and 40%. The method was similar to that adopted by Gonzalez-Andujar & Fernandez-Quintanilla [1991].

The sensitivity coefficient is defined as the ratio of the proportional change in the simulation results (adult plant density) to the proportional change in each input parameter:

$$\frac{\Delta APD}{APD} / \frac{\Delta parameter}{parameter}$$

A large sensitivity coefficient indicates that a small variation in the input parameter value will cause a large variation in the output of the model. The sensitivity coefficient was determined after 15 years of simulation, which was considered a long enough period over which to observe any long-term tendencies in the population. Two types of situations were considered: application of clodinafop along with zero tillage, and no weed control along with zero tillage [Table 4.1].

Table 4.1 The sensitivity of *P. minor* adult plant densities after application of clodinafop or no herbicides to changes in the values of the model's demographic input parameters after 15 years of simulation.

		Clodinafop			*No herbicide*		
Life stage	*Parameter*	*-10%*	*-20%*	*-40%*	*-10%*	*-20%*	*-40%*
Seedbank	*FSBZ*	2.11	2.33	2.77	0.26	0.27	0.27
	MORTR	26.3	54.1	2.26E2	1.43	1.66	2.36
Seedling	$EMRZ_1$	-4.60	-3.58	-2.32	1.63E-2	7.09E-3	2.96E-3
	$EMRZ_2$	-1.20	-1.14	-1.02	3.51E-2	2.75E-2	2.26E-2
	$EMRZ_3$	-4.74	-3.66	-2.34	-1.56	-1.42	-1.19
Midseason	*MIDMAX*	-6.29E-2	-8.90E-2	-0.13	-0.63	-0.66	-0.26
	$HEFF_1$	1.89E4	1.18E4	6.57E3			
	$HEFF_2$	1.09E2	2.74E2	4.47E2			
Adult plant	$SURV_1$	-4.75	-3.66	-2.34	-0.69	-0.71	-0.73
	$SURV_2$	-1.47	-1.37	-1.19	-0.19	-0.20	-0.20
	$SURV_3$	-4.78	-3.69	-2.35	-1.57	-1.42	-1.19
Seed production	*HI*	-7.52	-4.74	-2.50	-1.59	-1.45	-1.22
	SEEDW	21.2	76.0	1.25E3	0.82	0.89	1.08
	SSURV	-7.52	-4.74	-2.50	-1.59	-1.45	-1.22

After clodinafop application, adult plant densities were generally more sensitive to changes in input parameters than under herbicide-free conditions. Adult plant densities after continuous clodinafop application for 15 years were very low (0.047 plants m^{-2}) and relatively large changes in adult plant density due to changes in the values of input parameters are of little practical significance for *P. minor* control at such low densities. Adult plant densities were sensitive to changes in the values of biological parameters related to seedbank dynamics, such as individual seed weight (*SEEDW*) and longevity of seeds in the soil (*MORTR*). In addition, changes in herbicide efficacy ($HEFF_{1:2}$) of clodinafop had a dramatic impact on adult plant densities. This effect of varying herbicide efficacy on *P. minor* population dynamics has been studied in more detail below. Unlike *P. minor* individual seed weight, seed longevity depends on factors, such as cropping pattern and cultivation regime [Section 2.3.1], which can be manipulated by farmers.

4.4 Simulation of weed control strategies

Continuous Herbicide Use. Various chemical and cultural weed control scenarios were tested [Figure 4.5]. The model suggested that isoproturon application only slightly reduces *P. minor* densities compared with herbicide-free conditions. This is simply a reflection of the model's parametrisation with herbicide efficacy rates observed in fields infested by IPU-resistant *P. minor*. The use of zero tillage techniques was more beneficial for *P. minor* control than spraying 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 in combination with zero tillage, it would take 17 years until the weed density is below 1 plant ha^{-1} and can be considered eradicated. Eradication is therefore not a realistic weed control goal.

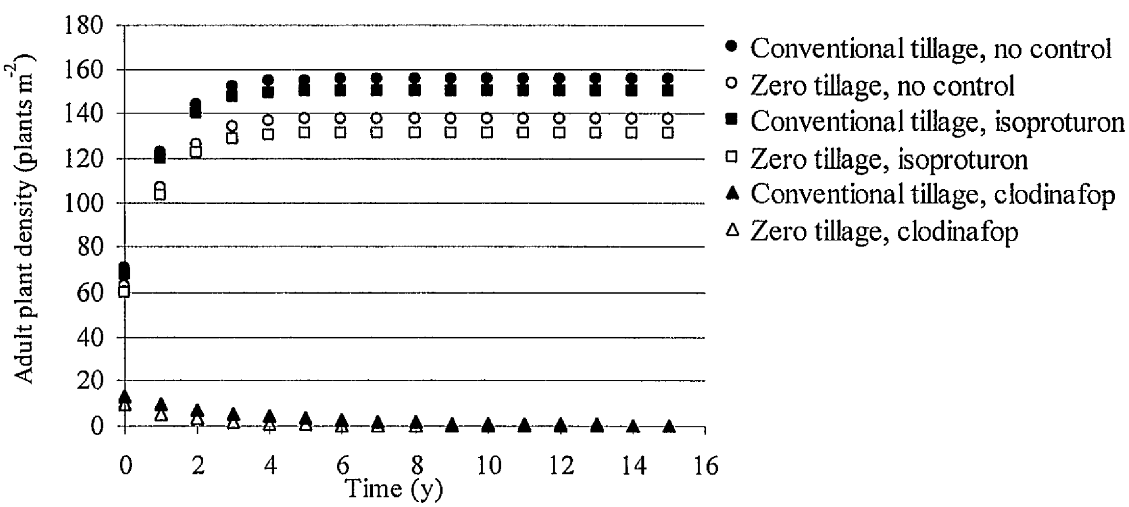


Figure 4.5 Effects of continuously applied herbicides and tillage regime on simulated *P. minor* demography.

Under herbicide-free conditions, the difference in adult plant density between zero tillage and conventional tillage could be attributed to variation in 3rd flush plant density [Figure 4.6a]. This difference in 3rd flush plant density may be related to the model's structure, which recognises density-dependent mortality for the 1st and 2nd flush, reducing the variation in seedling density between tillage systems. For the 3rd flush, no such mortality was observed in the field experiments and this mortality was not included in the model. However, it may well be possible that in reality 3rd flush plants are also subject to self-thinning, if seedling densities are very high. In this case, the model may overvalue the relative advantage of zero tillage reducing *P. minor* population size under herbicide-free conditions. After clodinafop application, it was also the 3rd flush plants that contributed most to the total adult plant population, but the difference in adult plant density between tillage systems could be attributed to variation in density of all flushes [Figure 4.6b]. Density-dependent mortality plays no role of significance after clodinafop spraying, as plant densities after spraying are very low. The simulated difference in adult plant population may therefore be a real effect, caused by variation in emergence rate between zero and conventional tillage systems.

Reduced Herbicide Efficacy. The sensitivity analysis already indicated that variations in the efficacy of the applied herbicides have a strong impact on the population dynamics of *P. minor* in competition with wheat. Farmers in Haryana often fail to obtain the optimum herbicide efficacy due to faulty herbicide application techniques. The model indicated that reducing the herbicide efficacy rate from 0.98 for the 1st flush ($HEFF_1$) and 0.95 for the 2nd flush ($HEFF_2$) to 0.90 or 0.80 for both flushes has a dramatic impact on *P. minor* population size in subsequent years [Figure 4.7]. The relatively large difference in plant densities between zero and conventional tillage systems when herbicide efficacy is poor can largely be attributed to variation in 3rd flush density, which may be an artefact of the model, as mentioned above. However, this does not weaken the general observation that population size is very sensitive to changes in herbicide efficacy rate.

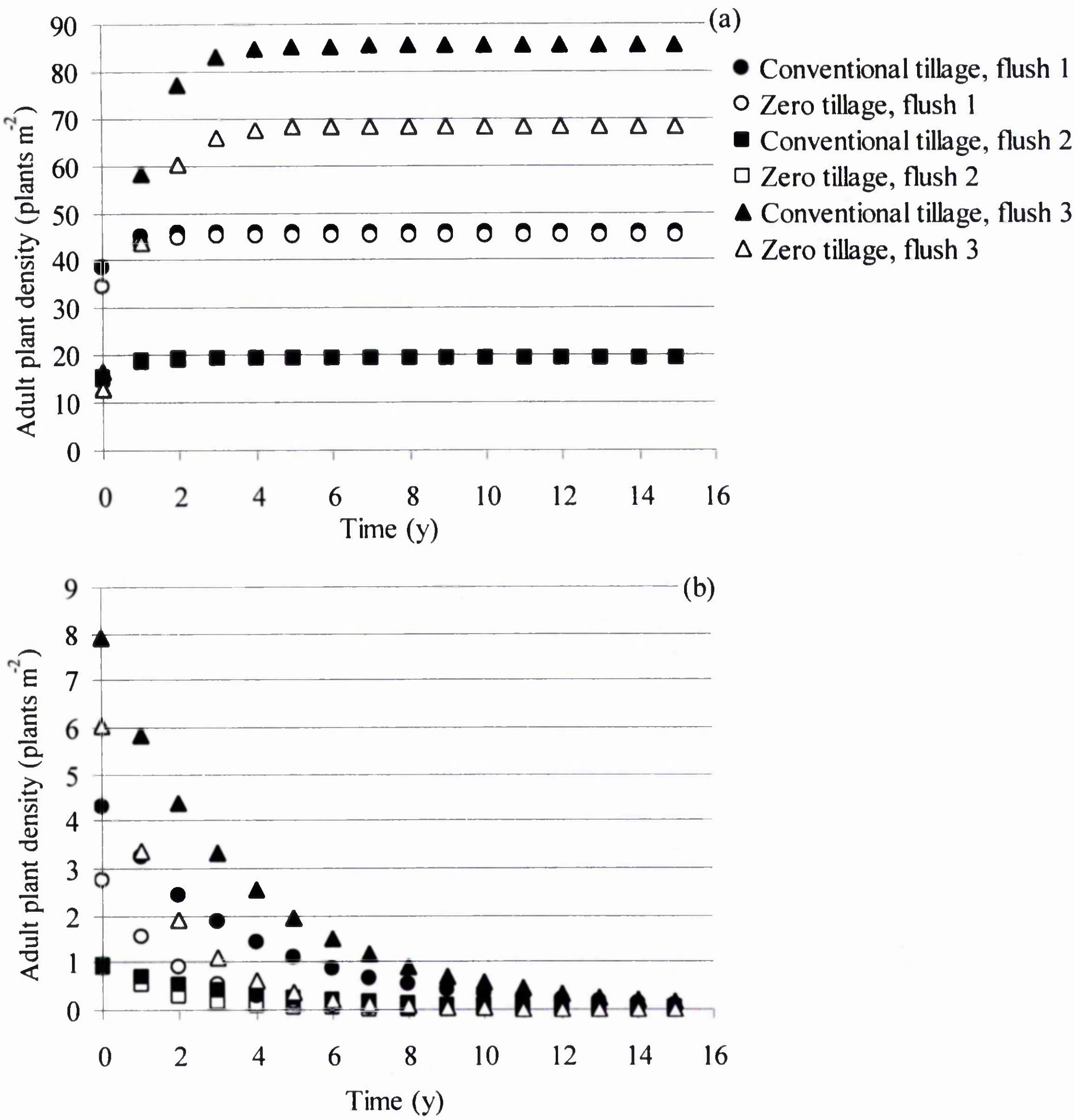


Figure 4.6: Simulated *P. minor* demography of 1st, 2nd and 3rd flush after:
(a) continuous application of no herbicides
(b) continuous application of clodinafop.

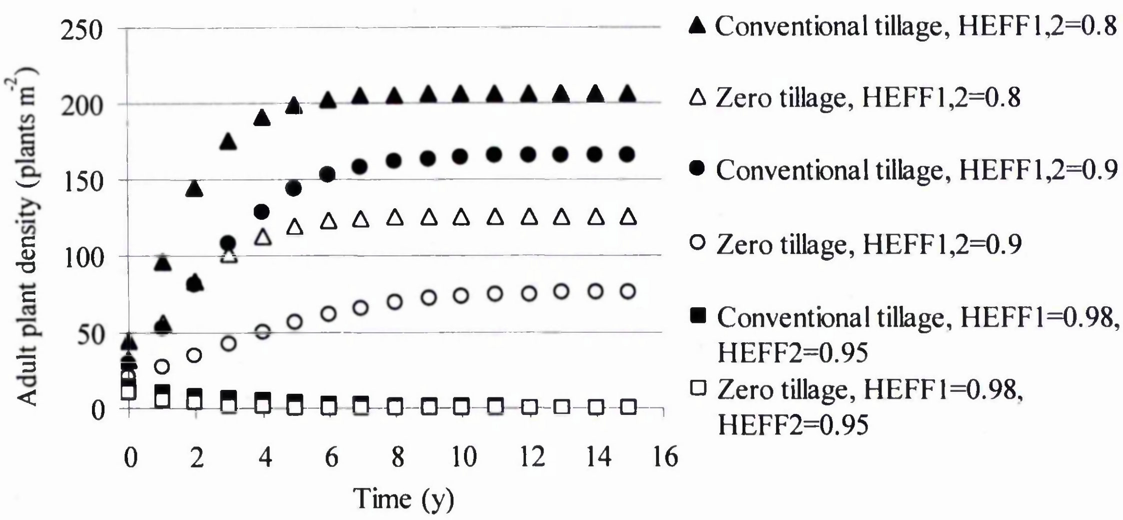


Figure 4.7 Effect of reduced efficacy of clodinafop for controlling the 1st (HEFF1) and 2nd flush (HEFF2) of seedlings on simulated *P. minor* demography.

Reduced Spraying Frequency. As herbicides are an expensive commodity for Haryana farmers, reducing the spray frequency may be a profitable weed control strategy. The model was used to explore possibilities for reducing the spray frequency, while keeping the adult plant densities below the threshold level of 10 plants m^{-2}. Farmers generally consider *P. minor* densities below 10 plants m^{-2} as an acceptable infestation rate. The model indicated that, in combination with zero tillage, herbicide application could be omitted once every four to five years [Figure 4.8]. Conventional tillage systems required more frequent spraying of herbicides. As the validation of this model showed that simulated outputs occasionally underestimate the reduction in *P. minor* populations after clodinafop spraying in conventional tillage systems, the difference in required spraying frequency between the two tillage systems may be less in the real world. The model suggested that spraying could be skipped for one year when the cumulative density of 1st and 2nd flush seedlings was below 23 seedlings m^{-2} or when the density of adult plants in the previous year was less than 1.0 plant m^{-2}.

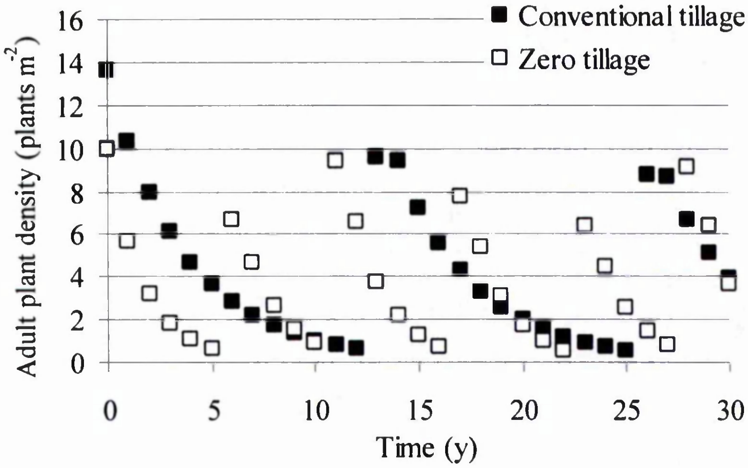


Figure 4.8 Simulated *P. minor* demography with a weed management strategy aiming to minimise the spray frequency, while maintaining adult plant densities below 10 plants m^{-2}.

Crop Rotation. Given the risk of the development of cross-resistance among IPU-resistant *P. minor* biotypes against newly introduced herbicides, there is a pressing need to reduce reliance on herbicides for weed control. An alternative weed control strategy was tested that curbed *P. minor* pressure through cropping rotations, alternating wheat with other winter crops preventing *P. minor* seed shed. In Haryana, wheat can be raised in rotation with one-season crops, such as berseem, mustard oil and vegetables, or with a two-year sugarcane crop. The model assumed that during cultivation of alternative crops, *P. minor* seeds in the soil show similar germination behaviour as in wheat, but germinated seeds fail to produce seeds at the end of the growing season.

The model indicated that alternating wheat with one-season crops without the use of herbicides is a viable strategy [Figure 4.9a]. After a sugarcane crop, productive cultivation of wheat under herbicide-free conditions is possible for two subsequent years, given that the initial seedbank densities are low (<1000 seeds m^{-2}) [Figure 4.9b]. The model suggested that these weed control strategies are only acceptable in combination with reduced tillage techniques. In both scenarios, the reduced emergence rate of *P. minor* seeds in fields under zero tillage is crucial to curb the *P. minor* populations later in the growing season.

Accordingly, the results indicated that wheat can be cultivated productively without the use of any herbicides in Haryana, but in this case, half the land suitable for wheat cultivation should be reserved for alternative winter crops.

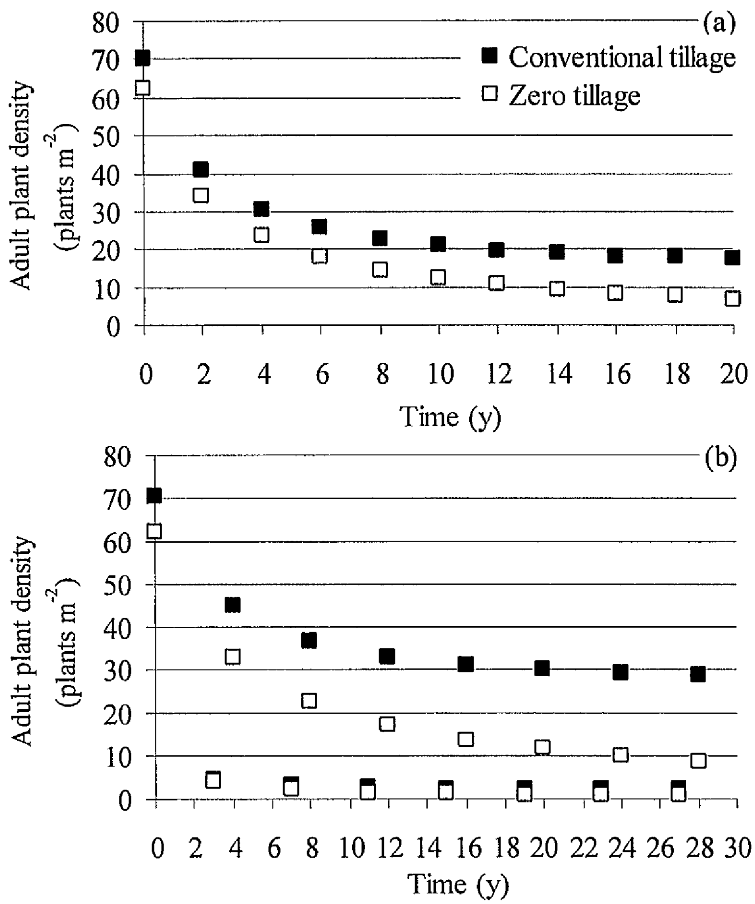


Figure 4.9 Simulated *P. minor* demography under herbicide-free conditions in competition with wheat alternated with:

(a) one-season non-cereal crops

(b) two-year sugarcane crop

4.5 Summary of the model results

The required calibration of the model with a seed survival parameter suggested that 75 to 85% of the newly shed seeds are lost by the beginning of the following growing season due to seed predation, decomposition and seed removal during wheat harvest, which is in line with results from the lifecycle studies. *P. minor* seed losses between seed shedding and seedling emergence the following season appear to be high, but have never been well studied. Manipulation of this mortality rate may offer a new component in an integrated weed control strategy.

The sensitivity analysis revealed that the model of the population dynamics of *P. minor* is highly sensitive to changes in the value of parameters related to soil seedbank dynamics, especially to changes in seed longevity, as well as changes in herbicide efficacy rate. Further exploration of the effect of changing herbicide mortality rate confirmed the strong impact of sub-optimal herbicides control efficacies on simulated *P. minor* population dynamics. Thus, the model indicated that improving herbicide application techniques among farmers should be a key priority for extension agents to reduce *P. minor* pressure in Haryana.

Simulations of *P. minor* population dynamics predicted that the benefits of reduced emergence rates in fields under zero tillage increases with reduced herbicide inputs, irrespective of the actual *P. minor* density. This suggests that the relative benefits of adopting zero tillage are higher for farmers who are unable to purchase effective herbicides and rely on alternative ways to keep *P. minor* in check. Moreover, model simulations suggested that controlling *P. minor* by alternating wheat with other one or two-year winter crops without the use of herbicides is a feasible strategy, but only in combination with zero tillage techniques. These results indicate that diversification of the rice-wheat cropping rotation may greatly benefit *P. minor* control and may reduce the reliance on herbicides for weed control. For a broader discussion of the results of the model in relationship with field observations and the practical implications for *P. minor* control, see Chapter 7: General Discussion.

CHAPTER 5: FARMING SYSTEM AUDIT

5.1 Introduction

Given the demand to maintain high grain yields in the face of production constraints such as *P. minor*, there is a pressing need to develop more sustainable crop production technologies for the Indo-Gangetic plains. The successful adoption of new technology will rely in part on its suitability for the system into which it is placed. To assess the suitability of an agricultural innovation for the farming system, thorough knowledge of the agronomic and socio-economic context of the innovation is required. Since no survey of the socio-economic status of rice-wheat farmers and the broader agronomic context of the *P. minor* epidemic has been reported for this region, the current audit was undertaken to attempt to identify the socio-economic and agronomic factors that could be related to the continuing pressure of the *P. minor* epidemic. In addition, farmers' willingness and ability to change present management practices in relation to the *P. minor* epidemic were assessed, which might be especially important in the light of determining the likelihood of adoption of more sustainable practices in the future.

5.2 Methodology

5.2.1 Audit contents and structure

A system audit was conducted consisting of two surveys of, respectively, 118 and 102 Haryana farmers interviewed at the end of the growing season in March-April 2000 and 2001. Wheat-growing farmers were surveyed in three geographically and edaphically distinct regions of Haryana. However, the audit was focussed on the two northern regions where *P. minor* control was most problematic. Within the regions, farmers working in the fields were randomly selected and interviewed. Most farms in Haryana are accessible by road and 98% of the approached farmers co-operated. Besides the emphasis that was placed on those regions that were most severely hit by the *P. minor* epidemic, the sample composition was also influenced by logistical factors such as poor roads and limited transport facilities. The questionnaire contained items related to farmers' socio-economic backgrounds, crop rotation, farm management, economics of wheat production and farmers' perceptions of *P. minor*. On each farm, the survey team estimated *P. minor* field densities (plants m^{-2}) by sampling. Since the surveys were conducted shortly before harvest, the observed densities of *P. minor* were for plants that had survived weed control. Wheat yield loss percentage due to *P. minor* was visually estimated in the field. For the questionnaire in its entirety, see Appendix IV.

5.2.2 Data handling

Farmers' wheat cultivation practices were summarised using survey data. Principal components analysis (PCA) [Digby & Kempton, 1987] was used to examine variation in the data and to search for evidence of clustering of the farmers into groups, which could be related to geographic location of the farmers. The analyses were conducted on correlation matrices constructed from the original data variates because these were of a mixture of types (binary, ordinal, and continuous) and measurement scales differed by orders of magnitude between variables. As the number of farmers interviewed in one of the three strata (region 3) was too small to be representative for the entire region, this group was excluded from most analyses, except for those linking farm characteristics to geographic location.

The relations between farm size, farm profitability, *P. minor* management and perception of *P. minor* as a problem for wheat production were examined. Socio-economic indicators were constructed from original questionnaire items. Four items were included in the initial indicator: farm size, number of cattle, availability of hired labour, use of tractors. A second indicator also included the additional item 'income source outside farming'. Since all of the individual variates were positively correlated, the indicators were calculated simply by summing the values for the individual variates after these had been standardised. This resulted in indicators that were positively correlated with socio-economic strength. The internal consistency of the socio-economic indicators was evaluated using Cronbach's α Test [Cronbach, 1951]. Based on their scores for the indicators, the sample of farmers was divided into four classes of increasing socio-economic strength. Using this stratification, the relationships between socio-economic indicators and variables associated with *P. minor* management, farm economics and access to information on farming were studied. The Cronbach α scores were calculated using Simstat (version 1.0 for Windows[1]). The data for farm profitability and access to information on farming were binary responses and the relationship between these and the socio-economic indicators was assessed using logistic regression assuming binomially distributed errors.

The ability of socio-economic indicators and scores of farmers' perceptions of weed control practices to predict the presence of serious infestations of *P. minor* was explored by canonical variates analysis (CVA) [Digby & Kempton, 1987]. CVA is also known by the name Linear Discriminant analysis. The sample of farms was divided into two groups on the basis of the *P. minor* density estimates collected during the survey. Farms on which the mean *P. minor*

[1] *Provalis Research Montreal, Canada, 5000 Adam Street, Montreal, QC, Canada, H1V 1W5*

density was >10 plants m^{-2} were considered to have a serious infestation, while those on which the mean density was ≤10 plants m^{-2} were considered not to have a serious infestation. Initially, the CVA was conducted using only those variates that comprised the second socio-economic indicator. A second CVA was performed in which the variates recording the farmers' rating of rotational crops and herbicides for *P. minor* control were added.

The presence of other weeds besides *P. minor* was related to soil type, crop rotation and region in a series of ANOVAs. Furthermore, the infestation rates of weed species recorded in this survey were compared with the those reported in a weed survey conducted in Haryana in 1990-1991. Using CVA, the abilities of the variables rotation, soil type, region, farm size and herbicide expenditure to predict the presence or absence of the three most abundant weed species besides *P. minor*, *Rumex maritimus*, *Avena ludoviciana* and *Chenopodium alba*, were examined.

Data on *P. minor* field densities and subsequent wheat yield loss allowed the construction of a curve describing wheat yield loss as a function of *P. minor* density. A rectangular hyperbola was preferred to other models describing yield loss related to weed density, such as quadratic and sigmoid models, since the rectangular hyperbola gave a relatively good statistical fit of the data and has two biologically meaningful parameters [Cousens, 1985a]. Yield loss curves for data collected in 2000 and 2001 did not differ significantly in a regression analysis fitting a rectangular hyperbola with year as group factor, and therefore, data from both years were lumped together. The mathematical expression of the applied model has been described in Section 3.2.

5.3 Results & Discussion

5.3.1 Summary of cultivation practices

Rice Harvest and Stubble Management. The surveyed farmers harvested the main rice crop between September and late October. In recent years, many farmers had intensified the cropping system by cultivating a short duration rice crop before the main rice crop, resulting in a late harvest of the main rice crop. The majority of the farmers (61%) burned rice stubbles remaining on the field, while 5% of the farmers incorporated stubbles into the soil and 34% of the farmers removed straw from the field, usually with the aim to use it as cattle fodder. Survey data suggested that rice straw burning helps to reduce the *P. minor* seed bank. While straw-burned plots had an average *P. minor* population of 15 plants m^{-2}, unburned plots had average populations of 40 plants m^{-2} (ANOVA, F_{pr}=0.011). This is in contrast with literature on the effect of burning on *P. minor* populations, reporting increased or equal *P. minor* populations after rice stubble burning, as compared with other means of stubble management [Malik & Singh, 1993; Brar *et al.*, 1995].

Soil Preparation. Farmers who did not practise zero tillage (89.5% of the surveyed farmers) ploughed, harrowed and planked their land before sowing. On average, farmers ploughed the land 1.9 times, harrowed 3.0 times and planked 1.9 times. It was estimated that 90% of the farmers used a tractor to perform the soil cultivation operations, while the remaining farmers used animal power; 57% of the surveyed farmers possessed a tractor.

Wheat Sowing. Farmers sowed wheat between late October and mid December with an average seed rate of 108kg ha^{-1}. In the survey, 20% of the farmers sowed wheat between late October and early November, 78% between early November and late November and 4% between late November and early December. Interviewed farmers usually did not remember the exact dates of sowing and could only indicate the period in which sowing was undertaken.

Only 10.5% of the surveyed farmers practiced zero tillage, while 36% of the farmers had not previously heard of zero tillage. No significant relationship was found between the adoption of zero tillage and soil type, region or *P. minor* density using ANOVA. Farmers practicing zero tillage mentioned they came into contact with the technique through neighbouring farmers or through university extension officers from HAU. Farmers practicing zero tillage were clustered around certain villages. In these villages, the technique of zero tillage was usually introduced by university extension workers on a small number of farms and consequently adopted by neighbouring farmers. The adoption was therefore positively correlated with extension received from university extension officers and slightly correlated with extension received from company representatives, and not with extension received through mass media (F_{pr} in ANOVA 0.01, 0.07 and 0.57 respectively).

Seed Handling. As wheat grain and *P. minor* seeds mature synchronously, *P. minor* seeds may be harvested along with wheat grain. If farmers use home-saved seeds in subsequent years, which was common practice among 82% of the farmers, these *P. minor* seeds may return to the soil seedbank. Anecdotal evidence in this survey suggested that the exchange of wheat seeds contaminated with *P. minor* seeds was a common mechanism by which *P. minor* biotypes infested previously uninfected areas. Seed stocks supplied and certified by seed breeders may also contain large numbers of *P. minor* seeds [Malik, 2002, pers. comm.]. Since wheat grain and *P. minor* seeds vary considerably in size, it is easy to separate wheat seeds from *P. minor* seeds through sieving. In this survey, 71% of the farmers sieved wheat seeds before sowing. Seed sieving was associated with low *P. minor* densities. While farmers sieving wheat seeds before sowing had an average *P. minor* field density of 10 plants m^{-2}, farmers who did not sieve had an average density of 25 plants m^{-2} (F_{pr} with ANOVA 0.034). This difference in *P. minor* density may be a direct result of reduced numbers of *P. minor* seeds returning to the soil seed bank after sieving. However, farmers practicing seed sieving may also be generally better, more careful farm managers than those who did not sieve, resulting in lower *P. minor* densities for seed sieving farmers.

Fertilisation. All farmers under survey applied nitrogen in the form of urea and di-ammonium phosphate during the wheat cultivation. Farmers used on average 169kg N ha^{-1}. Average phosphate application in the form of di-ammonium phosphate was 56kg P ha^{-1}. Di-ammonium phosphate and part of the urea was typically applied before or during wheat sowing, the remaining urea was broadcasted after the first irrigation (around 30 DAS). Potassium in the form of potassium muriate was used by 2.2% of the surveyed farmers. Farmyard manure (FYM) was added by 40% of the farmers under survey, usually 10-20t FYM $year^{-1}$ on 0.5-1ha. In simple regression analyses, no correlation was found between the amount of nitrogen applied and wheat yield. High nitrogen applications were associated with slightly higher *P. minor* densities (F_{pr}=0.083), stressing *P. minor*'s preference for nitrogen-rich soils. In an ANOVA test, the use of FYM was correlated with slightly higher wheat yields (F_{pr}=0.081) and lower *P. minor* densities (F_{pr}=0.030). The use of FYM may result in better growing conditions for wheat and improving the weed suppressing capacity of the crop. However, it is well possible that the interaction between the use of FYM, the nutrient and soil water balance, plant growth conditions and crop-weed interaction is far more complex.

Irrigation. To ensure sufficient soil moisture to prepare the land and allow wheat to germinate and emerge, most farmers applied a pre-sowing irrigation. If wheat is sown shortly after rice harvest, soil moisture levels may be sufficient to prepare the soil without applying additional irrigation water. The first post-sowing irrigation was typically applied 20-30 DAS. In total, farmers irrigated their fields 3-8 times during the wheat cultivation, depending on environmental factors such as soil type and rainfall. In the northern parts of Haryana, groundwater was usually pumped up for irrigation through tube wells, while in the southern parts, groundwater was often brackish and unsuitable for irrigation. Therefore, canal water originating from catchment areas in the southern Himalayas was preferred for irrigation in this area. Poor quality and availability of irrigation water was often mentioned as a major constraint for wheat production in these areas.

Herbicide Application. All farmers applied herbicides in wheat, except for those farming in the dry districts nearby Rajasthan, where *P. minor* pressure was low. Some farmers in heavily infested areas, managed to control weeds by rotating wheat with alternative winter crops and applied herbicides only occasionally. Due to the increasing incidence of IPU-resistance in *P. minor*, the newly introduced herbicides, sulfosulfuron, clodinafop-propargyl and fenoxaprop-P-ethyl, were the most popular herbicides [Table 5.1]. The newly introduced herbicides were more effective in controlling *P. minor* than IPU was. Metoxuron was applied by a small number of farmers, usually in combination with one of the other herbicides against *P. minor*. Some farmers reported good *P. minor* control using metoxuron, but mentioned phyto-toxicity to wheat as a major disadvantage of the herbicide. The herbicide 2,4-D, effective against broadleaf weeds, was applied by only 2.7% of the farmers, but given the increasing pressure of *Rumex maritimus* in the northern areas of Haryana, its use may increase in the near future.

Table 5.1 Herbicide use efficacy against *P. minor* and wheat yield reduction due to *P. minor* in Haryana (%, SE between parentheses).

Herbicide	*IPU*	*Sulfosulfuron*	*Clodinafop*	*Fenoxaprop*	*Metoxuron*	*None*
Usage	22.1	32.9	25.0	9.7	1.3	9.0
Efficacy	61.5 (3.8)	83.0 (1.4)	86.4 (1.6)	81.9 (2.6)	70 (7.1)	
Yield reduction	17.0 (3.8)	7.4 (0.8)	5.3 (0.8)	9.7 (1.6)	20 (7.1)	4.7 (1.7)

IPU was usually applied 20-35 DAS, directly after the first post-sowing irrigation. IPU was either manually broadcasted mixed with urea or sand, or sprayed with a knapsack sprayer after dissolving in water; the other herbicides were applied 30-50 DAS before the second irrigation using a knapsack sprayer. Some farmers (25%) hired labour to apply herbicides, others applied herbicides themselves. Most farmers (82%) used cut or hollow cone nozzles to spray herbicides. These nozzles have been designed for spraying insecticides and disperse herbicides irregularly over the crop, resulting in poor herbicide efficacy. Other farmers used appropriate flat fan nozzles to spray herbicides. It was observed in the fields that poor herbicide application techniques were a common cause of high *P. minor* densities.

Wheat Harvest. Wheat was harvested entirely manually by 54% of the farmers, other farmers made use of a combiner and harvested small plots of wheat manually to obtain straw. In this survey, the average wheat yield was 4.47t ha^{-1} in 2000 and 4.74t ha^{-1} in 2001, which is well above India's national average of 2.8t wheat ha^{-1} in 2000 [FAOSTAT, 2001]. Highest yields were obtained in the district of Fatehabad, where wheat yields typically varied between 5 and 7t ha^{-1}.

5.3.2 Regional structuring

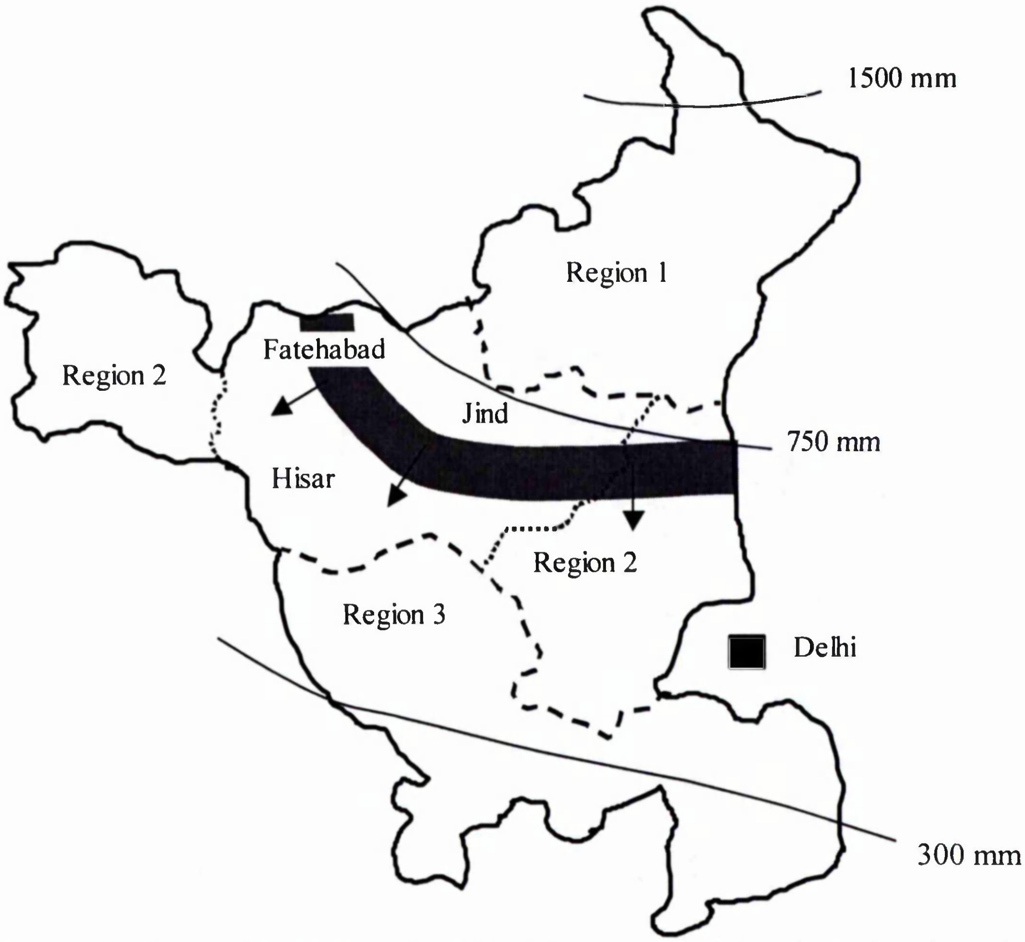
Out of a total of 220 interviewed farmers, 93 were located in the wet north-east of Haryana, region 1 (districts of Ambala, Karnal, Kaithal and Kurukshetra) [Figure 5.1], where the dominant rotation is rice-wheat [Table 5.2]. One hundred and ten farmers were located in the drier centre of Haryana, region 2 (districts of Panipat, Sonipat, Hisar, Jind, Fatehabad, Sirsa, Jhajjar and Rohtak), where besides rice-wheat, other rotations such as cotton-wheat or pearl millet-wheat are common. Seventeen farmers were located in the dry south-west region bordering Rajasthan, region 3 (districts of Bhiwani, Mahendra Garh and Rewari), where rice is replaced by pearl millet, vegetables, pulses or fallow.

Table 5.2 Regional characteristics of the wheat cultivation in Haryana.

	Region 1	*Region 2*	*Region 3*
No. of interviewed farmers	93	110	17
Annual rainfall (mm)	>750	300-750	<300
Presence of *P. minor* in wheat (%)	96	96	47
Reported IPU resistance (%)	95	55	0
Herbicide expenditure (€ ha^{-1})[1]	30.8 (0.87)	18.5 (1.27)	1.5 (0.70)
Wheat profitability (relative scale)[1]	3.6 (0.07)	2.9 (0.09)	2.4 (0.26)

Region 1 districts Ambala, Karnal, Kaithal & Kurukshetra
2 districts Panipat, Sonipat, Hisar, Jind, Fatehabad, Sirsa, Jahjjar & Rohtak
3 districts Bhiwani, Mahendra Garh & Rewari

[1] significant differences between regions with ANOVA, F_{pr} $p<0.001$



Border area between mostly resistant *P. minor* populations in north and mostly susceptible populations in south

Region 1 = districts Ambala, Karnal, Kaithal & Kurukshetra
2 = districts Panipat, Sonipat, Hisar, Jind, Fatehabad, Sirsa, Jhajjar & Rohtak
3 = districts Bhiwani, Mahendra Garh & Rewari

Figure 5.1 Map of Haryana indicating annual rainfall and geographic distribution of IPU-resistant *P. minor* biotypes.

Isoproturon Resistance. The problem of IPU-resistant *P. minor* biotypes worsened towards the wetter regions. In region 1, 95% of the farmers reported *P. minor* IPU-resistant biotypes in their fields, while none of the farmers in region 3 was certain of having resistance. In region 1 many farmers have been using IPU since the late 1970s [Malik, 1995], while the surveyed farmers in region 3 generally reported that *P. minor* had invaded their fields only recently, and they had been using IPU for less than five years, or did not use any herbicides at all.

Herbicide Expenditure. Farmers who knew that IPU-resistance was a problem on their farms, (in regions 1 and 2) had often switched to alternative, more expensive herbicides. At the time of the surveys, IPU application cost on average €8.90 ha^{-1}, while the alternative herbicides cost around €36 ha^{-1}. This, together with the time course of IPU-resistance development, explains why herbicide expenditure increased from south to north, from region 3 to 1.

Wheat Profitability. In region 1, where the pressure of resistant *P. minor* and herbicide costs were highest, average profitability of the wheat cultivation was also highest. In the drier regions, where *P. minor* pressure and herbicide costs were lowest (region 3), farmers reported that profitability of the wheat cultivation was constrained by high costs for pumping up ground water and poor availability and quality of ground water.

Principal Components Analysis. For climatic and historical reasons, farms from the three regions differed from each other in cropping pattern and field management. Therefore, *P. minor* densities, evolutionary stage of herbicide resistance and farmers' perception of the *P. minor* problem also varied from region to region. Although no a priori classification of the farms into regions is imposed in using PCA, it was possible to distinguish the farmers from various regions surveyed in year 2000 from each other [Figure 5.2] indicating that regional variation is a dominant structure in the data matrix. Results for PCA conducted on the data matrix for 2001 gave similar distinction among regions. Figure 5.2 shows the result of a PCA including the following variables:

1. Farm size
2. Herbicide expenditure
3. *P. minor* density
4. Number of irrigation during the wheat season
5. Wheat seed rate
6. Farmer's ranking of the severity of the *P. minor* problem compared to other constraints during wheat cultivation.

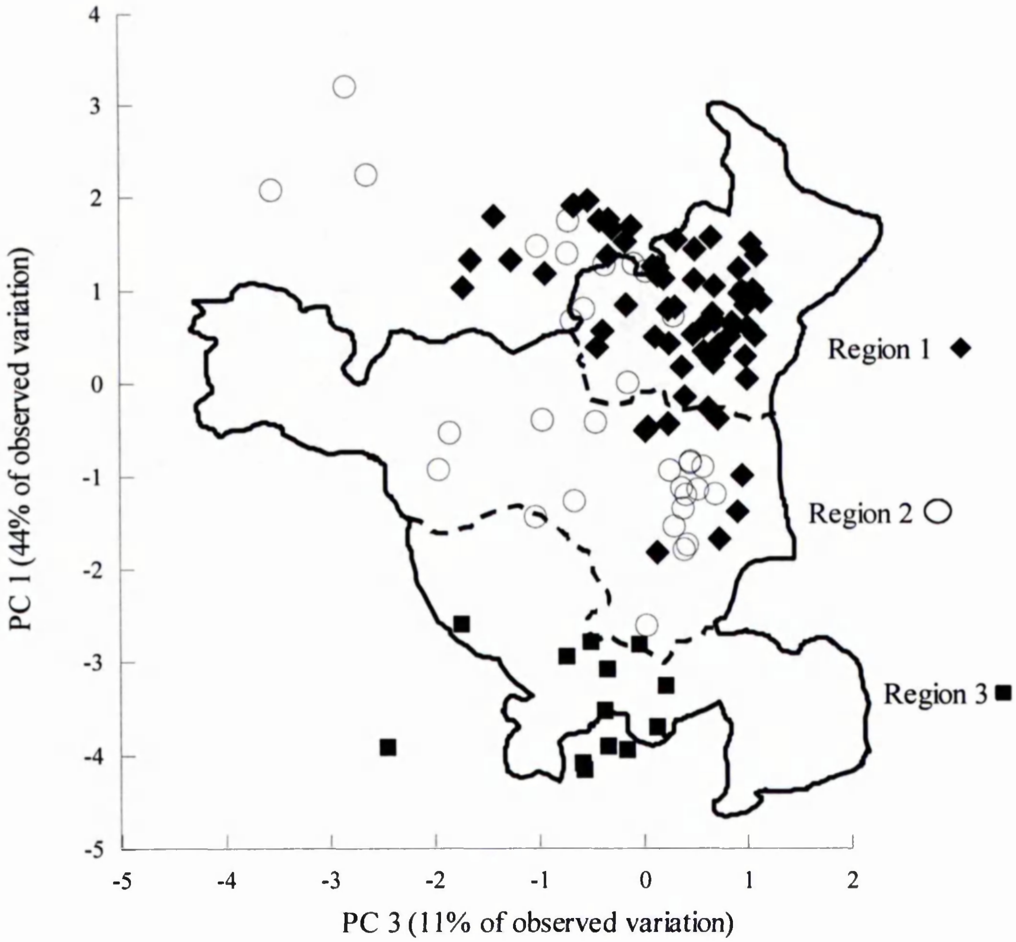


Figure 5.2 Scatter plot of Principal Components 1 and 3 for farmers from different regions after Principal Components Analysis, plotted over a map of Haryana. Farmers from region 3 were clearly separated from farmers from other regions by PC1, while the distinction between farmers from region 1 and 2 was not absolute.

Principal Component (PC) 1, accounting for 44% of the total variation, was associated with the discrimination of farmers in region 3 from the other two regions by large negative scores on PC 1. The latent vectors of PC1 [Table 5.3] indicated that farmers in region 3 had small landholdings, low herbicide expenditure, applied a high number of irrigations, a high wheat seed rate and ranked *P. minor* as a relatively unimportant problem for the profitability of the wheat cultivation compared with other constraints. A high number of irrigations and a high wheat seed rate in region 3 were probably related to the dry, sandy soil conditions. *P. minor* field density was an unimportant variable for determining the scores for PC1, probably because in both region 1 and 2, where most farmers were situated, high *P. minor* densities occurred.

Table 5.3 Characteristics of PC 1, 2 & 3 in principal components analysis

	PC 1	*PC2*	*PC 3*
% Variance accounted for	44.4	19.0	13.7
Latent vector			
1. Farm size	0.28	0.34	-0.88
2. Herbicide expenditure	0.54	0.02	0.13
3. *P. minor* field density	-0.03	-0.85	-0.39
4. Number of irrigations	-0.42	0.15	-0.18
5. Wheat seed rate	-0.43	-0.20	-0.09
6. Farmers' ranking of *P. minor*	-0.52	0.30	-0.10

Farmers in regions 1 and 2 were partly differentiated by the PCA, but the distinction was not absolute. Some farmers in region 2 had high PC1 scores and were therefore plotted along with those from region 1. All farmers in region 2 with PC1 scores higher than 1 had characteristics which were typical for region 1 farmers, such as large landholdings, resistant *P. minor* biotypes and high herbicide costs. Six out of nine of these farmers were situated near the village of 'Lalodha', which has a relatively long history of intensive rice-wheat cultivation in comparison with other villages in region 2 and was one of the earliest to report problems with IPU-resistant *P. minor*. Likewise, farmers in region 1 with low PC1 scores had relatively small landholdings, reported no problem with resistance, or were not sure if resistant was present, and 50% of them still used IPU, so had characteristics typical for farmers in region 2.

The latent vector of PC2 suggested that *P. minor* field density was the main variable determining farmers' scores for PC2 [Table 5.3]. All farmers had PC2 scores between –2 and 2, except for five outliers with high negative scores, which could all be characterised as having extremely high *P. minor* densities in their fields (>200 plants m^{-2}). PC3 scores were strongly affected by farm size [Table 5.3]. Farmers with low scores for PC3 (<2.0) [Figure 5.2] all possessed relatively large landholdings (>16ha). High PC1 scores for farmers in region 2 (thus showing characteristics associated with farmers in region 1) often coincided with high scores for PC3, suggesting that farm size is positively associated with high herbicide expenditures and the occurrence of IPU-resistant *P. minor* biotypes.

Since the survey focussed on regions 1 and 2 where *P. minor* control is most problematic and the 17 farmers interviewed in region 3 were not considered representative for this entire region, only farmers from region 1 and 2 have been included in the remaining analyses of this chapter.

5.3.3 Weed control options

To assess farmers' preferences for weed control options, they were asked to value the usefulness of various *P. minor* control methods [Table 5.4]. Herbicides were the most popular weed control tool, with high costs as the only drawback mentioned by some farmers. Soil cultivation techniques to control *P. minor* were popular among farmers who had been exposed to zero tillage. This technique, which is a recent innovation for Haryana, allows farmers to directly drill their wheat into the stubble of the previous rice crop, giving reduced *P. minor* densities [Section 3.3.2] Farmers using rotational crops to break the lifecycle of *P. minor* considered crop rotation as a good weed control tool. However, poor profitability and limited market opportunities constrained the use of rotational crops. The possibility to use wheat cultivars with high weed suppressing abilities was unknown among most farmers, except for those who raised traditional tall wheat varieties (2% of the interviewed farmers). Farmers' cultivar preferences were mainly determined by yield characteristics, leading to a situation where 78% of the farmers grew the same wheat cultivar (PBW343). Manual weeding was mainly popular with small farmers and on lightly textured soils. Manual weeding is labour intensive in a period when labour availability is constrained and therefore only feasible for small farmers. In addition, manual weeding is more efficient on soils light or medium in texture [Walia & Gill, 1985].

Table 5.4 Farmers' rating of weed control practices (relative scale).

Weed Control Tool	Farmers' Rating
Herbicides	0.74
Cultivation techniques	0.55
Rotational crops	0.53
Wheat cultivars	0.35
Manual weeding	0.34

0 = Poor usefulness for weed control
1 = High usefulness for weed control

5.3.4 Farm size

The severity of *P. minor* pressure not only varied among regions, but also among farms. If farms were structured by farm size, highest *P. minor* densities were found on small farms (2-4ha) [Table 5.5]. With some exceptions, very small farmers (0-2ha) had low *P. minor* densities, as they could effectively control weeds through crop rotations and manual weeding. Many very small farmers grew vegetables and a relatively large area of berseem as a winter crop. These cultivations were only possible on small plots of land, because of their labour intensity and limited market opportunities. Labour scarcity limited the possibilities of manual weeding on slightly larger farms (>2ha). These farms relied more on herbicides for weed control. Some of the small farms (2-4ha) were not prosperous enough to purchase effective herbicides, or not well aware of the possibilities new herbicides offer, and these farms were worst hit by the *P. minor* epidemic. Most large farms (>4ha) obtained good *P. minor* control using effective herbicides.

Table 5.5 The relationship between farm size and *P. minor* density in Haryana. Small farmers owning 2-4ha of land had highest *P. minor* densities in their fields (SE between parentheses).

Farm size	*0-2ha*	*2-4ha*	*4-8ha*	*8-12ha*	*>12ha*
No. farmers interviewed	33	57	41	26	46
P. minor (plants m^{-2})	18.5 (6.4)	42.2 (13.4)	14.8 (2.8)	14.1 (3.0)	15.6 (3.6)

5.3.5 Farm profitability

If farms were structured by farmers' views on the profitability of their farms, it was clear that farmers considering their farm profitability lowest had highest *P. minor* densities and *vice versa*, emphasising the importance of *P. minor* as a production constraint [Table 5.6]. High *P. minor* densities should probably be attributed to low herbicide expenditures. Farmers with poorly profitable farms and high *P. minor* densities spent little money on herbicides. Surprisingly, those farmers with the least profitable farms and high weed densities rated *P. minor* as a less important constraint for wheat cultivation than farmers with highly profitable farms and low weed densities. Farmers with poorly profitable farms often blamed other factors, such as high prices for electricity and fuel, low State-guaranteed minimum support prices for wheat, shortage of irrigation water or salinity of ground water, for the poor profitability of wheat cultivation.

One of the underlying explanations for the poor profitability of the wheat cultivation on certain farms is likely to be the lack of capital required to purchase inputs for weed control. As poor weed control results in low wheat yields, little income and poor availability of capital in the subsequent year, this is a self-enforcing mechanism. In addition, farmers' lack of knowledge of non-chemical ways to control *P. minor* and their inability to improve their wider socio-economic environment may also be among the underlying reasons that explain poor profitability of the wheat cultivation.

Farmers' ratings of the severity of *P. minor* as a constraint on profitability and their decisions to use cheap, less effective herbicides were not always based on sound economic reasoning. In areas invaded by IPU-resistant biotypes, farmers applying IPU had an average *P. minor* density of 100 plants m^{-2}, while farmers using one of the newly introduced, more expensive herbicides had densities of 14 plants m^{-2}. Yield reduction due to *P. minor* in IPU-treated fields was on average 38%, and 10% for fields sprayed with new herbicides. This is equivalent to a yield gain of around 1.13t ha^{-1} for fields treated with one of the new herbicides. With a State-guaranteed minimum support price for wheat of €138 ton^{-1} in 1999/2000, financial gain was €156 ha^{-1}, while the extra costs for switching from IPU to one of the new herbicides were roughly €27 ha^{-1}. So, the rate of return for money invested in new herbicides was almost 6:1. Anecdotal evidence collected during farmer interviews revealed that many farmers continue using IPU due to a lack of readily available cash, ignorance about the phenomenon of resistance, poor availability of alternative herbicides, and unfamiliarity with economic calculations. In some interviews it was apparent that farmers were hardly aware which herbicides they were using and placed complete trust on the local pesticide dealers (known locally as 'middlemen') supplying them. Other farmers, complaining about the efficacy of the purchased herbicides, found it difficult to avoid the monopoly position of the local middlemen, giving them a crucial position in weed management.

Table 5.6 Relationship between farm profitability and farm size, *P. minor* density, herbicide expenditure and farmers' rating of the severity of *P. minor* compared with other constraints during wheat cultivation (SE between parentheses).

Profitability	*Very low*	*Low*	*Moderate*	*High*	*Very high*
No. farmers interviewed	5	40	77	72	9
Farm size (ha)	2.8 (0.72)	6.9 (0.93)	7.0 (0.74)	8.6 (1.08)	11.7 (1.86)[1]
P. minor density (plants m^{-2})	152 (65)	32 (12)	14 (2.4)	17 (3.6)	9.0 (5.2)[2]
Herbicide costs (€ ha^{-1})	9.1 (4.6)	15.6 (2.1)	21.3 (1.6)	27.9 (1.3)	30.8 (1.7)[2]
Farmers rating of *P. minor*[4]	0.50 (0.13)	0.63 (0.04)	0.69 (0.02)	0.74 (0.02)	0.80 (0.00)[3]

[1 2 3] Significance level of relationship between profitability and relevant variable, generated by ANOVA
[1] $F_{pr} = 0.009$ [2] $F_{pr} < 0.001$ [3] $F_{pr} = 0.018$

[4] 0 = *P. minor* rated as an unimportant constraint
1 = *P. minor* rated as an important constraint

5.3.6 Socio-economics

Socio-economic Indicators. The standardised Cronbach α scores for the initial indicator which included the variables farm size, number of cattle, availability of tractors, availability of hired labour was 0.81; this is a relatively high value and indicates that the four variables were related to the same underlying construct. When the variate 'income source outside farming' was included, the internal consistency of the indicator was reduced with a standardised Cronbach α of 0.76. The variable 'income source outside farming' was obviously related to the wider financial position of the farmer. Although this variable was positively correlated with the scale of farming, *i.e.* large-scale farmers with a high mechanisation level were likely to have additional income besides farming, 'income source outside farming' measured a slightly different underlying construct than the other variables. However, since all five variable were related to the farmers' socio-economic position and positively correlated with each other, the second indicator was used for further analyses.

Socio-economic Class and Weed Management. Farmers' ratings of herbicides, and to a small extend soil cultivation techniques, were positively related to farmers' socio-economic strength [Table 5.7]. These control tools require relatively high investment and mechanisation levels, and were therefore valued more highly by farmers with a strong socio-economic position. The use of wheat cultivars with high weed suppressing abilities can be seen as a low-input method of suppressing *P. minor* and was therefore rated more highly by farmers with a poor socio-economic position. The rating of crop diversification and manual weeding to combat *P. minor* was not related to socio-economic class. Farm profitability was strongly correlated with farmers' socio-economic position. Socio-economically successful farms were also the most profitable farms.

Table 5.7 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 (2001 data, SE between parentheses).

Socio-economic class[1]	*1*	*2*	*3*	*4*	*Significance*[2]
Rating of weed control practices[3]					
Herbicides	0.59 (0.06)	0.74 (0.05)	0.74 (0.05)	0.84 (0.07)	0.035
Cultivation techniques	0.47 (0.04)	0.58 (0.04)	0.54 (0.05)	0.64 (0.06)	0.134
Wheat cultivars	0.30 (0.02)	0.28 (0.02)	0.26 (0.03)	0.21 (0.01)	0.082
Profitability[4]	0.59 (0.02)	0.66 (0.02)	0.64 (0.03)	1.00 (0.04)	0.007
Information sources					
University	11 (6.0)	8.8 (4.9)	28 (9.2)	53 (13)	< 0.001
Other government	18 (7.4)	24 (7.4)	40 (10)	80 (11)	< 0.001
Agro-chemical company	46 (9.6)	59 (8.6)	64 (9.8)	93 (6.7)	0.024
Radio / TV / Newspaper	86 (6.7)	85 (6.2)	96 (4.0)	93 (6.7)	not significant

[1] from class 1 to 4 increasing socio-economic strength

[2] Relationship between relevant variable and socio-economic class, F_{pr} tested with ANOVA

[3] 0 = poor usefulness for weed control
1 = high usefulness for weed control

[4] 0 = poor farm profitability
1 = high farm profitability

Farmers' socio-economic position also affected their access to information on farming. Farmers from higher socio-economic classes were more likely to report that they received information from university extension officers, workers from other governmental institutions and agro-chemical companies than farmers from lower socio-economic classes [Table 5.7]. The poorest farmers were more likely to receive information from company representatives than university or other government extension officers. The preference of state extension officers to work with resource-rich farmers is a well known pattern, since they tend to be more innovative, better educated, easier to approach, and have improved access to capital making it easier for them to implement advice offered by extension officers [Röling, 1988]. Farmers belonging to different socio-economic classes made equal use of broadcast media to obtain advice on farming, which suggested these media may be a more effective way to spread simple advice on farming through the entire farming community than the use of extension officers.

5.3.7 Predicting **Phalaris minor** *infestations*

A Canonical Variates Analysis based solely on the set of variables associated with farmers' socio-economic position was used to predict the occurrence of high *P. minor* densities [Table 5.8, CVA1]. The predictive value of these variables was rather low, with only 62% of the farmers correctly classified (as having mean weed densities of either > or ≤ 10 plants m^{-2}). Farmers with high positive CVA scores were classified as farmers with a serious *P. minor* problem. The latent vectors in Table 5.6 show that the variables 'income source outside farming', 'the presence of a tractor' and a high 'number of cattle' were related to low *P. minor* densities, while 'the availability of hired labour' was associated with higher *P. minor* densities. The low score of the latent vectors for 'farm size' indicated that this variate was not linearly correlated to the presence of yield loss due to *P. minor*, also shown in Table 5.5.

When the variates coding farmers' rating of the usefulness of rotational crops and herbicides to control *P. minor* were added, the percentage of correctly classified farmers increased to 75% [Table 5.8, CVA2]. Farmers who highly rated the usefulness of rotational crops and herbicides to control *P. minor* were associated with low field *P. minor* densities, stressing the effectiveness of herbicides and crop diversification for the control of *P. minor*. Wrongly classified farmers in CVA2 were not equally spread out over the survey area. While in the central-western districts of Hisar, Jind and Fatehabad only 62% of the farmers were correctly classified, this figure was 89% for the remaining areas [Figure 5.1]. The districts Hisar, Jind and Fatehabad had high average *P. minor* densities and contained border areas between resistant and non-resistant *P. minor* populations. This suggested that in areas recently infested by resistant *P. minor*, farmers were equally affected by the epidemic, irrespective of their socio-economic position or opinion about weed control tools. In areas where resistance has been present for several years or areas without a history of resistance, it was easier to predict which farmers would suffer from high *P. minor* infestations based on either willingness to invest in weed control measures or the availability of resources for control. The fact that socio-economic factors were less effective in predicting farms with a serious *P. minor* problem in an area without a history of resistance is consistent with the idea that the invasion of IPU-resistant biotypes is equivalent to the introduction of a new weed species. During the early period after the infestation develops, all farmers were equally affected. Later, a predictable pattern emerged where larger farmers with access to money and technical innovations managed to control the weed, while others failed.

Table 5.8 Latent vectors of Canonical Variate Analysis.

Standardised variable	*CVA 1*	*CVA 2*
Income source outside farming	-1.276	-0.857
Availability hired labour	0.326	0.231
Presence of tractor	-0.437	-0.143
Number of cattle	-0.093	-0.031
Farm size	0.000	-0.006
Rating of rotational crop for *P. minor* control		-0.369
Rating of herbicides for *P. minor* control		-0.445
% correctly classified farmers	62%	75%

5.3.8 Other weeds

Though *P. minor* was the most noxious winter weed of Haryana, various other weeds had infested the wheat cultivation as well. Occurrence of weed species infesting more than 10% of the total number of farms under survey was often related to factors such as region, soil type and crop rotation [Table 5.9]. The factors region, soil type and crop rotation identified in Table 5.9 were interrelated. Region 1 hosts mostly clay and clay loam soils with rice-wheat rotations, region 2 mostly clay loam and silty clay loam soils with rice-wheat, as well as cotton-wheat and millet-wheat rotations, and region 3 mostly sandy and sandy loam soils with rotations such as millet-wheat and fallow-wheat. *Rumex maritimus* was mostly abundant on heavy, clayish soils in rice-wheat rotations in region 1 and 2; *P. minor* preferred sandy loam soils or soils heavier in texture in rice-wheat as well as cotton-wheat rotations. The presence of weed species such as *Chenopodium album*, *Avena ludoviciana*, *Lathyrus aphaca* and *Vicia sativa*, was greater on sandier soils in mixed rotations in regions 2 and 3. Weed species such as *Melilotis indica* and *Convolvulus arvensis* were not related to any region, soil type or crop rotation.

Comparison of the average incidence of weed species in 2000-2001 with data collected in a weed survey of Haryana conducted in 1990-1991 [Singh *et al.*, 1995], showed that *P. minor* and *R. maritimus* had increased in abundance, while the incidence of other weed species was stable or reduced [Table 5.9a]. Many factors that may influence the weed flora have changed over the last decade, such as adoption of alternative herbicides, an increasing use of fertilisers, irrigation water and tractors, and it is hard to indicate which factors were driving the changing weed spectrum. IPU has a wide spectrum of weed control including broadleaf weeds, while the control range of the new herbicides is confined to a limited number of grass weed species. Therefore, increasing use of new herbicides was expected to coincide with an increase in incidence of broadleaf weeds over time. While this may be true for *R. maritimus*, the drastically reduced incidence of other broadleaf weeds, such as *C. album* and *Anagallis arvensis*, contradict this hypothesis.

Only three weed species, apart from *P. minor*, have been noticed to cause wheat yield loss in the field, namely *R. maritimus*, *C. album* and *A. ludiviciana*. Yield losses up to 30% due to *R. maritimus* were reported, while yield losses due to *C. alba* and *A. ludoviciana* were always less than 5%. Canonical variate analyses, conducted to explore the abilities of environmental and farm-related variables to predict the presence of weed species, correctly classified the presence or absence of *R. maritimus*, *A. ludoviciana* and *C. album* on respectively 73%, 74%

Table 5.9a Regional distribution of weeds in Haryana in 2000-01, compared with the State-average in a survey conducted in 1990-1991 (% of infested farms).

Weed species	*2000-2001* *region 1*[1]	*region 2*[1]	*region 3*[1]	F_{pr}[2]	*2000-2001 average*	*1990-1991 average*
Phalaris minor	96	96	47	*<0.001*	93	67
Rumex maritimus	74	45	35	*<0.001*	56	30
Melilotis indica	47	61	29	*0.02*	53	47
Chenopodium album	15	48	49	*<0.001*	35	76
Avena ludoviciana	2	32	76	*<0.001*	23	64
Convolvulus arvensis	12	35	59	*<0.001*	23	18
Anagallis arvensis	19	26	24	0.50	23	38
Lathyrus aphaca	2	27	0	*<0.001*	15	12
Vicia sativa	5	22	0	*<0.001*	13	15

Table 5.9b Effect of soil type on the incidence of weeds in Haryana (% of infested farms).

	Sandy	*Sandy (clay) loam*	*Clay loam*	*Clay*	F_{pr}[2]
Phalaris minor	56	97	96	83	*<0.001*
Rumex maritimus	38	43	71	67	*<0.001*
Melilotis indica	25	57	53	50	0.134
Chenopodium album	56	43	26	0	*0.004*
Avena ludoviciana	63	27	11	50	*<0.001*
Convolvulus arvensis	0	38	14	0	*<0.001*
Anagallis arvensis	25	27	21	0	0.415
Lathyrus aphaca	0	25	7.9	0	*0.001*
Vicia sativa	6.3	23	5.9	0	*0.003*

Table 5.9c Effect of rotation on the incidence of weeds in Haryana (% of infested farms).

Weed species	*rice-wheat*	*rice-wheat cotton-wheat*	*cotton-wheat millet-wheat*	F_{pr}[2]
Phalaris minor	98	100	69	*<0.001*
Rumex maritimus	68	49	23	*<0.001*
Melilotis indica	53	56	49	0.795
Chenopodium album	23	44	69	*0.004*
Avena ludoviciana	11	28	59	*<0.001*
Convolvulus arvensis	15	38	36	*0.001*
Anagallis arvensis	18	31	33	0.067
Lathyrus aphaca	9.2	36	13	*<0.001*
Vicia sativa	9.2	26	15	*0.024*

[1] Region 1 = districts Ambala, Karnal, Kaithal & Kurukshetra
2 = districts Panipat, Sonipat, Hisar, Jind, Fatehabad, Sirsa, Jahjjar & Rohtak
3 = districts Bhiwani, Mahendra Garh and Rewari [Figure 5.1]

[2] Effect of regions on weed incidence tested with ANOVA

and 69% of the 220 farms included in the analysis [Table 5.10]. For all three weed species, high positive scores for the latent vector of the CVA were associated with the presence of the weed. The presence of *R. maritimus* was associated with high herbicide costs and presence of rice-wheat rotations. High herbicide costs may be related to the use of expensive, selective herbicides for the control of IPU-resistant *P. minor* that cease to control broadleaf weeds. The presence of *A. ludoviciana* was associated with southern regions, other rotations than rice-wheat and low herbicide expenditure. The presence of *C. album* was associated with other rotations than rice-wheat, southern regions and high herbicide costs. *A. ludoviciana* and *C. album* are both weeds that flourish in drier regions in cotton-wheat and millet-wheat rotations. Soil type and farm size were relatively unimportant variables for predicting the weeds' presence.

Table 5.10 Latent vectors of CVA for three weed species, positive values were associated with the presence of weeds.

Variate	*R. maritimus*	*A. ludoviciana*	*C. album*
Herbicide costs	1.00	-0.26	0.47
Soil type[1]	0.11	0.11	-0.19
Farm size	0.14	0.19	0.24
Rotation type[2]	-0.28	0.31	0.73
Region[3]	0.17	0.82	0.61
Correctly classified	73%	74%	69%

[1] soil type 1 = sandy; 2 = sandy (clay) loam; 3 = clay loam; 4 = clay

[2] rotation 1 = rice-wheat
2 = rice-wheat / cotton-wheat
3 = cotton-wheat / millet-wheat / fallow-wheat

[3] region 1 = districts Ambala, Karnal, Kaithal & Kurukshetra
2 = districts Panipat, Sonipat, Hisar, Jind, Fatehabad, Sirsa, Jahjjar & Rohtak
3 = districts Bhiwani, Mahendra Garh and Rewari

Weed species in wheat in Haryana infesting less than 10% of the surveyed farms included: *Medicago denticulate, Silene conoidea, Poa annua, Fumaria parviflora, Coronopus didymus, Polypogon monspeliensis, Euphorbia dracunculoides, Trigonella polycerata, Rumex* *spinosus*, *Spergula arvensis*, *Spergula denticulata*, *Carthamus oxycantha*, *Asphodelus tenuifolius* and *Circium arvensis*.

5.3.9 Quantifying crop weed interaction

The relationship between *P. minor* field density and subsequent wheat yield loss was quantified using a rectangular hyperbola [Figure 5.3]. When the model was fitted to the survey data in a regression analysis, the following parameter values were found (SE between parentheses):

A = 39.8 (2.6)   I = 0.98 (0.002)

The parameter values suggested that maximum wheat yield loss due to *P. minor* was 39.8% and yield loss per weed plant at very low weed densities was 0.98%. The percentage of variance accounted for in the correlation analyses (R^2) was 62.1%. When *P. minor* densities exceeded 150 plants m^{-2}, residual values were high, indicating that wheat yield loss as a function of *P. minor* density at high weed densities is more difficult to predict than at low weed densities. This could be explained by the field observation that some extremely dense *P. minor* populations mainly existed of second and third flush plants causing relatively little harm to the crop, while other dense populations mainly existed of first flush plants causing high wheat yield loss.

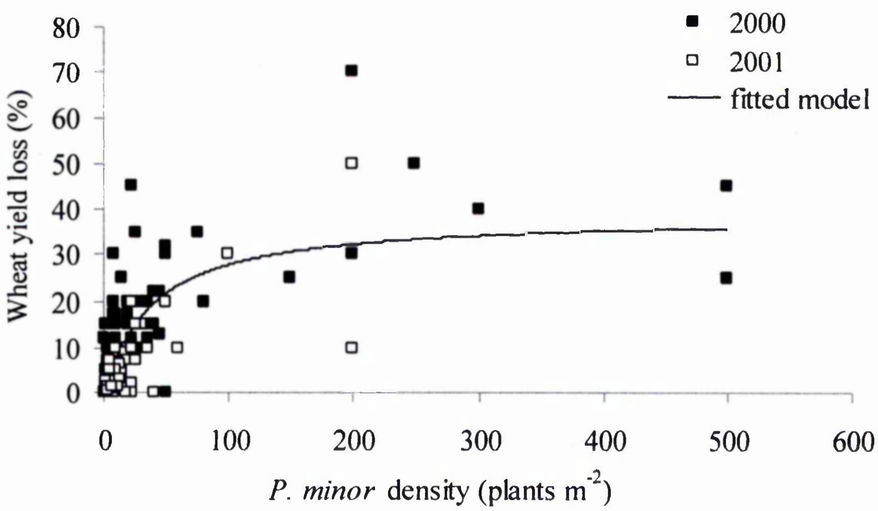


Figure 5.3 Relation between *P. minor* field density and wheat yield loss, observed values and fitted regression model (rectangular hyperbola).

CHAPTER 6: A MODEL FOR THE ADOPTION OF AGRICULTURAL INNOVATIONS IN STRUCTURED POPULATIONS

6.1 Introduction

6.1.1 Modelling adoption processes

The adoption of novel technologies and techniques is a major concern in agricultural extension and development work. It is a common experience that the adoption of an apparently useful agricultural technology is slower than predicted, or desired, by extension agents [Röling, 1988]. One of the reasons behind this delay is the pro-innovation bias of much extension research. That is the implication that an innovation should be diffused rapidly, and that innovations should not be re-invented, nor rejected [Rogers, 1995]. Related to the pro-innovation bias is Röling's [1988] criticism on the general practice of the progressive farmer strategy in agricultural extension. In this strategy, change agents approach progressive farmers to deliver extension on relevant innovations, after which the innovation is supposed to spread to other segments of the farming community through word-of-mouth communication. Because farming populations are not homogeneous, rewards for innovations change over time, extension messages are distorted over time, and for numerous other reasons, innovations often fail to spread to all segments of the farming population. Traditional extension strategies tend to fail to give sufficient attention to socio-economic structuring and the degree of interconnectedness of the farming community, and to differences in psychological characteristics of individual farmers.

Diffusion models may assist in gaining an understanding of the driving variables behind diffusion processes and allow, at least in theory, the prediction of the future adoption rate of innovations. Many models of diffusion currently used in agricultural extension research are heavily simplified representations of the reality of diffusion processes [Röling, 1988] and have little ability to predict future adoption of innovations. An exception is the Bass model [Bass, 1969], which is a mathematical model originally derived for marketing science. Most of the model's applications are in the field of marketing, but its use in agricultural science is justified by the assumption that the launch of a new product on the market can be compared with the launch of an innovation in a farming community. Akinola [1986] provides a clear case study of the use of the Bass model in studying the adoption of pesticide use by Nigerian cocoa growers.

The Bass model recognises two sources of technological innovations. In agricultural extension, adoption of innovations through *external* factors is adoption initiated by factors outside the farming community, for instance by extension agents or mass media promotion. Adoption through *internal* factors is adoption resulting from inter-personal communication between farmers. Farmers adopting an innovation through external factors are sometimes referred to as (real) innovators, while farmers adopting through internal factors are referred to as imitators.

The Bass model and similar models deal with the adoption process at the population level. Such models also neglect several important factors determining the adoption rate of innovations and reflect the pro-innovation bias of most other diffusion research. The Bass model, for example, assumes that (1) the market potential of new products/innovations remains constant over time, (2) the nature of the innovation does not change over time, (3) the diffusion of new innovations is independent of other innovations and (4) the diffusion process is not influenced by marketing/promotion strategies, such as changing product prices, changes in advertisements, etc. [Mahajan *et al.*, 1990]. As noted above, in real situations the market potential of innovations changes over time and distortion of information and reinvention of innovations changes the extension message and the nature of novel techniques.

In addition, the distinction the Bass model makes between adoption through either external or internal factors may not reflect the reality of how farmers decide to adopt or reject an innovation. Few farmers decide to adopt a new farming technique solely based upon information received from mass media or extension officers. Rogers [1995] estimates that the percentage of innovators in any population is between two and five per cent. External factors may create interest in and awareness of innovations, but the actual decision to adopt a new technique is usually not taken by the majority of farmers until information and practical experience from peer-farmers is received. Hence, external factors may facilitate the spread of innovative agricultural techniques through interpersonal communication, but are not convincing on their own.

Many of the limitations of the Bass and similar phenomenological models can be overcome if a micro-level modelling approach is taken [Chatterjee & Eliasberg, 1990]. However, although parameter estimation for micro-level models is straightforward in principle, it is far more time consuming due to greatly increased data requirements than for phenomenological[1] models which deal with population level processes. Here we present a compromise approach which incorporates heterogeneity among individual adopters while modelling the innovation-adoption process at the population level. The model is developed in ecological terms in an attempt to provide a cross-disciplinary exchange of concepts from production ecology to management science and *vice versa.*

Before a description of the derivation of the model and an analysis of its performance, the history of zero tillage is explained in the next section to show the complexity of the context in which its adoption is taking place. The use of the technique of cognitive mapping [Kosko, 1992] is illustrated with reference to the rice-wheat system to show its value in capturing the

[1] The term *phenomenological* is used rather than the term *aggregate* which is more common in the economics/management science literature to avoid confusion with the ecological term *aggregation.*

potential dynamics of complex systems. The development of cognitive maps for the rice-wheat system and their use in predicting the dynamics of model parameters is discussed in more detail in later sections of the chapter.

1.2 *History of the adoption of zero tillage in Haryana*

The first on-farm demonstrations of zero tillage in wheat in Haryana were conducted in 1996 by Haryana Agricultural University. The extension workers involved in promoting zero tillage concentrated their efforts on a dozen villages, where good relationships with progressive farmers already existed. Many of these farmers belonged to the Sikh caste. They are traditionally innovative and resource-rich farmers, who are often more able and willing than farmers from other castes to try out new farming techniques. Incentives, in the form of free use of zero-till machinery and free herbicides, were provided to farmers joining zero tillage demonstrations. At the time zero tillage was introduced, farmers in Haryana were having difficulty controlling the weed IPU-resistant *P. minor*. The pressure that IPU-resistant *P.minor* exerted on farm income contributed to the farmers' willingness to experiment with zero tillage. On the other hand, the complex mechanism by which zero tillage affects *P. minor* population size was not well understood. This made many farmers sceptical about the use of zero tillage as a means to control *P. minor*, impeding their willingness to adopt. Another hindrance to the acceptance of zero tillage was the widely held conviction that extensive soil cultivation operations before wheat sowing are a necessity for good crop establishment. However, after the first on-farm demonstrations showed a considerable reduction in *P. minor* pressure and similar yield as fields under conventional tillage, willingness to adopt increased [Singh & Panday, 2002].

In 1998, alternative herbicides for the control of *P. minor* were launched on the Indian herbicide market, greatly improving the control of isoproturon-resistant *P. minor*. Consequently, the introduction of new herbicides decreased the relative advantage of zero tillage over conventional tillage by reducing *P. minor* pressure. However, by 1998 it had been realised that adoption of zero tillage gave a considerable reduction in soil cultivation and labour costs. This economic advantage soon became the main driving variable behind the adoption of zero-tillage, and from 1998 onwards, diffusion of zero tillage through interpersonal communication began to take off. The innovation was spreading to other farmers living in the neighbourhood of those villages initially targeted by the extension workers. Farmers could now purchase their own zero-till drill through a local manufacturing company and no further incentives were provided to farmers to adopt zero tillage. At this stage, a high degree a trialability (farmers could easily try out the innovation by cultivating a small area of their land with a hired zero-till drill) and a high degree of observability of the innovation in the field favoured rapid diffusion. Diffusion through interpersonal communication soon became a more important means of spreading the innovation than the activities of relatively small team of university extension workers. The size of the extension team involved in promoting zero tillage existed of around ten people, while the size of the farmer population potentially adopting zero tillage is several million

Extension about zero tillage was also provided through mass media broadcasts, for example through television and radio programs on farming and farming newsletters. These media were highly effective in creating awareness of zero tillage among the entire farmer community. However, farmers, who were aware of the innovation through mass media, generally lacked willingness to adopt until further information and practical experience from their peers was received. Presently, zero tillage is widely adopted in the surroundings of the villages where university extension workers introduced the innovation, while outside these areas, the fraction of adopters in the population is still low. In areas with a low adoption rate, many farmers are aware of the availability of zero tillage, but lack confidence in the technique. The university extension team may still play an important role in accelerating the rate adoption by organising demonstrations of zero-tillage in these areas.

The likelihood of adoption depends not only on farmers' geographic location, but also on their socio-economic position. The main economic advantages of zero tillage, *e.g.* reduced soil cultivation and labour costs, are higher for farmers with larger landholdings and a higher degree of mechanisation, as compared with small farmers using animal draft power. Small farmers already have minimal soil cultivation costs, and hiring a tractor and a zero-till drill may increase cultivation costs. In addition small farmers have relatively more family labour per hectare of land available than large farmers and are therefore less interested in the time and labour savings resulting from adopting zero tillage.

The degree of interconnectedness of the farming community in Haryana appears to be another relevant factor in the adoption of zero tillage. In common with other village-based rural communities strong family ties and the prevalent caste system divide farmers into social groupings [Jodhka, 1998]. Farmers have strong contacts with peer-farmers belonging to the same grouping and tend to communicate less with farmers belonging to other groupings. Some groupings had a tradition of innovativeness, while others are more conservative. As mentioned above, Sikh farmers were among the first farmers to adopt zero tillage. Generally, Sikh farmers intensively exchange information on farming and the technique, after its introduction, rapidly diffused among Sikh farmers. Farmers from other castes were slower to adopt zero tillage, irrespective of their geographic location. Apparently they had less contact with Sikh farmers who had adopted zero tillage and were less willing to accept information on farming from Sikh farmers.

In the next sections, the new diffusion model is derived and the use of cognitive mapping for capturing a quantitative description of the farming system is described. The final section of the paper discusses the implications of the model for diffusion of innovations in a development setting.

.2 Materials & Methods

2.1 *Derivation of a new diffusion model for adoption of technology*

6.2.1.1 The Bass model

Starting point of the new model is the Bass model. The Bass model distinguishes diffusion through external factors (mass media and change agents) and internal factors (interpersonal communication). The number of new adopters resulting from interpersonal communication is described as a constant fraction (β) of the product of farmers who have adopted (A) and those who have not adopted (N-A). According to the model, the cumulative number of adopters, adopting through *internal* factors follows a sigmoid curve with time.

The numerical equation for the number of adopters through internal factors can be written as:

$$\frac{dA}{dt}_{\text{internal}} = \beta \cdot A_t \cdot (N - A_t) \qquad (6.1)$$

Where:

A_t is the total number of adopters at year t;

A_{t+1} is the total number of adopters at year $t+1$;

N is the maximum potential number of adopters;

β is the coefficient of internal diffusion; indicating the chance of adoption as a fraction of the possible interactions between non-adopters (N-A) and adopters (A) at time t.

Equation 6.1 is the familiar logistic growth curve, which is widely applied in studies of biological population dynamics [May, 1973; Begon *et al.*, 2000]. The adoption rate through external factors is modelled as a fraction (α) of the farmers who have not adopted:

$$\frac{dA}{dt}_{\text{external}} = \alpha \cdot (N - A_t) \qquad (6.2)$$

Where α is the coefficient of external diffusion; *i.e.* the fraction of the total of farmers who have not adopted, adopting through external factors.

The coefficient of external diffusion is relevant in situations in which the initial adoption of innovations is induced by extension agents and mass media promotion, targeting all farmers who have the potential to adopt the innovation (*N*): that is, if $A_0 = 0$ then $A_1 = \alpha \cdot N$. Since the adoption rate through external factors is proportional to the number of non-adopters, the rate will be highest when no farmers have adopted and will decrease over time with growing number of adopters.

The Bass model combines equation 6.1 and 6.2 and may be written as:

$$\frac{dA}{dt} = \alpha \cdot (N - A_t) + \beta \cdot A_t \cdot (N - A_t) \qquad (6.3)$$

Sultan *et al.* (1990) found that for fifteen different applications of the Bass model, the average coefficient of external diffusion (α) was 0.03, while the average coefficient of internal diffusion (β) was 0.38. This suggests that the diffusion process is affected more by factors such as word of mouth than by mass media influence.

6.2.1.2 A novel diffusion model

Diffusion processes which rely on personal contact to spread an innovation are analogous to infectious processes in the spread of a disease; indeed Rogers [1995] uses the word “contagious” to describe the adoption/diffusion process. In common with many simple models of disease and population dynamics, the commonly used diffusion models assume homogenous mixing of the population through which the disease (or innovation) is spreading. However, one of the key factors in determining the rate of such processes is the contact rate between those who have already adopted (infected individuals in the case of disease) and those who have not already adopted (uninfected individuals). The contact rate between adopters and non-adopters, for a fixed number of adopters, is lower if those adopters are aggregated physically and/or socially, so that a large number of their interpersonal contacts are with other adopters. It is this aspect of the diffusion process which current models do not take into account and for which the new model has been derived. Alternative modelling approaches, which consider contact rates directly, are widely used in human health studies and would be another potential starting points for the derivation of adoption/diffusion models [see for example, Black & Singer, 1987].

The effect of non-homogenous mixing (or aggregation) on population dynamic processes has been widely considered in the applied ecology literature [Nachman, 1981; Waggoner & Rich, 1981; Madden *et al.*, 1987; Kuno, 1988; Yang & Te Beest, 1992; Hughes *et al.* 1997]. These studies present various mathematical models population dynamic processes which account for non-homogenous mixing of infected and uninfected individuals. Some of these models make use of Lloyd's Index of Patchiness (LIP) to account for the effects of aggregation on the rate of population increase. LIP was originally intended as a measure of the patchiness of a meta-population of plants or animals and is derived from the variable 'mean crowding' [Lloyd, 1967]. Mean crowding is defined as "the mean number per individual of other individuals in the same quadrat". If the quadrat size coincides with the individual's ambit, mean crowding is the average number of individuals with which an individual interacts. In sampling studies LIP is calculated as the ratio of mean crowding to mean density per quadrat.

To transfer the use of LIP to diffusion of innovations in agriculture, 'mean crowding' is taken to be the number of other adopters an individual adopter interacts with within his/her ambit. An adopter's ambit is taken to be the area within which the adopter interacts with other farmers, and within which diffusion of an innovation might occur as a result of personal contacts. In this case it is difficult to define precisely what geographical area an ambit constitutes. For the purposes of the present study, an individual's ambit is taken to be a village and its immediately surrounding farms.

As interpersonal communication is the dominant factor accounting for the speed and shape of the diffusion of an innovation [Rogers, 1995], Bass's equation for diffusion through interpersonal communication is used as the starting point for the development of the new model. The coefficient of external diffusion is omitted for two reasons. First, interest in the present context is in studying the dynamics of uptake of innovations after they have been introduced. Secondly, as already noted above, during diffusion of agricultural innovations, such as zero tillage, few farmers adopt as a direct result of contact with change agents or other external influences. However, extension *via* mass media is helpful in facilitating interpersonal diffusion by raising awareness of innovations and this aspect of its impact and is included in the section dealing with cognitive mapping, in which we consider variables affecting the attractiveness of an innovation and the rate of adoption.

To adapt the diffusion model for aggregation effects, we need to redefine equation 6.1, describing the adoption curve for innovations. The following equation has the advantage that it is less sensitive to changes in population size compared with equation 6.1, in which the innovation rate increases exponentially with increasing population size.

$$\frac{dA}{dt} = r \cdot A \cdot (1 - \frac{A}{N}) \qquad (6.4)$$

Where:

r is a rate parameter summarising the capacity of the innovation to spread, analogous to the coefficient of internal diffusion (α);

$(1 - \frac{A}{N})$ is the population fraction of non-adopters.

A high value for LIP means that the adopters are aggregated. This aggregation decreases the number of contacts an adopter has with non-adopters. This is equivalent to saying that increasing levels of aggregation reduce the effective population fraction of non-adopters. If LIP has a value, x say, an adopter would interact on average with x times as many adopters as expected under a random pattern of adopters (i.e. under homogeneous mixing of adopters and non-adopters). Stating this formally we can include LIP in equation 6.4 as follows:

$$\frac{dA}{dt} = r \cdot A \cdot (1 - \frac{LIP \cdot A}{N}) \qquad (6.5)$$

If LIP is stable over time, the maximum number of adopters corrected for LIP, N', would behave as follows:

$$N' = \frac{N}{LIP} \qquad (6.6)$$

According to equation 6.6, at high values of LIP the diffusion process would come to an end at relatively low levels of adoption. However, ecological analyses of diffusion processes [Yang *et al.*, 1991; Yang & TeBeest, 1992; Madden *et al.*, 1987] show that LIP changes over time. Transferring these ecological results to the present context we might expect that aggregation levels (*i.e.* LIP) to decrease as the fraction of adopters increases. Therefore, LIP should be calculated as a function of the number of adopters. This leads to a general form of the new diffusion model given in equation 6.7.

$$\frac{dA}{dt} = r \cdot A \cdot \left(1 - f(A) \cdot \frac{A}{N}\right) \qquad (6.7)$$

Finally, it is necessary to define a form for the function $f(A)$ in equation 6.7. Unfortunately, there are limited data available on the behaviour of LIP over time for ecological data and none that we know of for diffusion processes in the current context. However, as an initial attempt to derive $f(A)$ we may proceed heuristically.

It is known that the maximum value of LIP occurs in the hypothetical situation in which adopters and non-adopters are completely segregated. The maximum value of LIP is, then, determined by the ratio of the maximum number of adopters per village to the number of potential adopters per village. When the number of adopters (A) approaches the maximum number of adopters (N), adopters are no longer aggregated (relative to the non-adopters), and therefore LIP will approach the value of 1. The theoretical maximum value of LIP at any value of A can thus be defined as:

$$LIP_{\max}(A) = \frac{\frac{N}{q} - 1}{\frac{A}{q}} = \frac{N - q}{A} \qquad (6.8)$$

where:

q is the total number of villages.

If the number of individuals per village is relatively large, LIP_{max} approaches $\frac{N}{A}$. For example, if the number of individuals per village exceeds 100, the approximation of LIP_{max}, as $\frac{N}{A}$, deviates less than 1% from the real value of LIP_{max}. Since in the rural community in Haryana a farmer's ambit usually exists of several hundred farmers, it would be reasonable in the current case to estimate LIP_{max} as $\frac{N}{A}$.

Having established that the actual value of LIP for any A varies between 1 and the maximum value of LIP for that value of A, we now assume that the function LIP(A) is a constant fraction of $LIP_{max}(A)$ minus an asymptote $LIP_{max} = 1$. If the value for LIP is known at a certain adoption fraction (A/N), LIP as a function of A can be calculated as:

$$LIP(A) = 1 + \frac{LIP_{\left(\frac{A}{N}\right)} - 1}{LIP_{\max\left(\frac{A}{N}\right)} - 1} \cdot \left(\frac{N}{A} - 1\right) \tag{6.9}$$

Substitution of equation 6.9 into equation 6.7 leads to the expression for the new diffusion model:

$$\frac{dA}{dt} = r \cdot A \cdot \left[1 - \left(1 + \frac{LIP_{\left(\frac{A}{N}\right)} - 1}{LIP_{\max\left(\frac{A}{N}\right)} - 1} \cdot \left(\frac{N}{A} - 1\right)\right) \cdot \frac{A}{N}\right] \tag{6.10}$$

6.2.1.3 The new model applied for adoption of zero tillage

The performance of the model was tested for the adoption of zero tillage using data from the farmers' survey (Chapter 5). Only data from those districts within Haryana where farmers practised zero tillage were used. In these districts, overall adoption rate of zero tillage, sometimes practised along with other tillage techniques, was 19%. The average adoption rate of 19% was probably a slight overestimation of the actual adoption rate, due to bias related to the interviewers' preference to conduct interviews with progressive farmers in villages with relatively high socio-economic standards. Data from 25 villages, where two or more farmers were interviewed, were included to test the effect of aggregation on the adoption rate of zero tillage.

Of the 25 villages providing data used to parameterise the model, 11 villages hosted farmers using zero tillage, while in the remaining 14 villages, none of the interviewed farmers had implemented zero tillage, indicating that adopters were aggregated. The average adoption fraction in villages with at least one person practising zero tillage was 0.50, while the average adoption fraction of all 25 villages was 0.23. Assuming that the average number of farmers per village in villages where zero tillage was practised was equal to the average number of farmers per village in villages without zero tillage, and bearing in mind that the number of farmers per village was relatively large (>100), LIP at the given adoption fraction approaches: $\frac{0.50}{0.23} = 2.17$.

At an adoption fraction of 0.23, the approximation of LIP_{max} is 4.35 (from equation 6.8).

The total number of adopters, *N*, was estimated as the product of the number of villages (25) and the average number of farmers per village. This second value was estimated as 500, based on information gathered from local farmers and HAU extension staff, giving a value for *N* of 12500.

The cumulative number of adopters in the 25 villages and the rates of adoption were examined for four situations:

(1) $LIP_{\left(\frac{A}{N}=0.23\right)} = 2.17$ (aggregation based on observation)

(2) $LIP_{\left(\frac{A}{N}=0.23\right)} = 1.0$ (no aggregation, equivalent to homogenous mixing)

(3) $LIP_{\left(\frac{A}{N}=0.23\right)} = 1.085$ (50% aggregation compared with situation 1)

(4) $LIP_{\left(\frac{A}{N}=0.23\right)} = 3.255$ (150% aggregation compared with situation 1)

For comparison of the qualitative effects of different levels of aggregation on the rate and progress of adoption, the rate coefficient, *r*, in equation 10 was set to 0.38 (based on the results of Sultan *et al.* [1999] reported above). Numerical results, using parameter estimates for *r* and *N* based on survey data are described in Section 6.3. Adoption progress curves for equation 10 were obtained by numerical integration using a Runga-Kutte method implemented in Mathcad (version 2001i (Professional), Mathsoft Inc. Cambridge MA 02141, USA).

.2.2 Cognitive map construction for examining the dynamics of the rate coefficient *r*

The rate coefficient *r* can be considered as a parameter expressing the attractiveness of the innovation, analogous to the infectiousness of a disease, and is likely to depend on Roger's [1995] attributes of innovation rate: relative advantage, compatibility, complexity, trialability and observability. Also, mass media may affect the diffusion coefficient *r*, by facilitating interpersonal diffusion and so increasing the 'infectiousness' of the innovation.

It might be expected, by analogy to the epidemiological context, [Plank, 1963; Campbell & Madden, 1990] that *r* will not be constant over time. Sufficient data are not available to undertake a quantitative analysis of the question of how *r* will vary over time. This situation is quite common in the development of models in systems analysis and we present here a method which allows initial progress to be made based on expert opinion. The method has the advantage of focussing the attention of the researcher on the interactions which occur between different components of the system under investigation.

A cognitive map represents logical and causal connections between actions, objects or concepts which together describe a larger entity, system or concept. In a cognitive map, boxes of various shapes typically represent the concepts, objects or actions and causal relationships between them are represented by arrows. The arrows are annotated with '+' and '-' signs to indicate causal increase or decrease respectively. In cases where the relative strength of the causal relationship can be estimated the '+' and '-' signs can be replaced by values between -1 and 1 to produce what is known as a Fuzzy Cognitive Map (FCM) [Taber, 1991; Kosko, 1992, 1993]. The numerical values can be related to linguistic quantifiers such as; 'never', 'sometimes', 'often', 'always', 'little', 'some', 'a lot', which makes the technique easy to use in gathering expert opinion. The data to be translated into an FCM can be gathered either from face-to-face interview or from written material in which the concepts under consideration are discussed. An FCM represents a view of the way in which a particular feature of the world works and can be used to make inferences about the expected behaviour of this feature through the application of some relatively straightforward matrix algebra.

The first step is to translate the causal connections in the map into a square matrix. If the map contains n concepts, the matrix will have n rows and n columns, one row and one column representing each concept. Each column of the matrix contains the values of the causal effects of a concept on each of the other concepts in the map (which are represented by the n rows of the column). In order to generate inferences from the FCM, an $n \times 1$ vector of initial values is multiplied to the matrix to generate a vector of output states. Repeated multiplication of the output vector to the matrix may result in a stable pattern of activation of the concepts emerging (known as a stable limit cycle) or a single stable steady state may be obtained (in which the *pattern* of activations of the concepts remains constant), or chaotic patterns of activation may arise [Taber, 1991; Kosko, 1992]. The technique is directly analogous to the construction and interpretation of community projection matrices in population ecology [May, 1973; Caswell, 2001]. A simple example based on expert opinion of the issues which determine a farmer's decision to plant potatoes in preference to wheat in the rice-wheat system is shown in Figure 6.1a. The causal statements underlying the FCM are given in Table 6.1. The expert opinion predicts a cyclical oscillation in the production of potatoes within the system as the feedback between supply and price fluctuates. Examination of the output from the cognitive map [Figure 6.1b] shows that the qualitative aspects of the predicted system behaviour agree with the stated expert opinion.

Table 6.1 Expert opinions on the factors determining the long-term use of potato as an alternative crop in the rice-wheat system of Haryana.

Statement no.	*Statement*
1.	Sometimes as a result of the problems associated with rice-wheat farmers plant potatoes
2.	A high potato price will make farmers try potato as a crop because the price makes the rice-wheat problems more apparent

Table 6.1 (cont.)Expert opinions on the factors determining the long-term use of potato as an alternative crop in the rice-wheat system of Haryana.

3.	A high potato price makes potato an attractive crop in itself and makes farmers plant potato
4.	When lots of farmers plant potatoes, a potato glut occurs
5.	A potato glut reduces the price of potato, leading to fewer farmers planting them next year
6.	*The situation described in statements 1-5 leads to a cyclic pattern of boom and bust in the planting of potato in the rice-wheat system*

In the present study, discussions regarding the factors influencing the uptake of zero tillage technology in Haryana were conducted with various local experts and farmer groups in Haryana in 1999, 2000 and 2001. From field notes made by the project team during these discussions a set of causal statements was produced from which the FCM shown in Figure 6.2 was produced. The list of factors (states) in the FCM is given in Table 6.2 together with the initial activation levels in the projections. The set of causal statements is given in Table 6.3, with their weights. The aim of the map FCM was to capture the main factors which affect the attractiveness of zero tillage and might therefore affect the value of the parameter, r, in the diffusion model.

Table 6.2 Initial levels of activation in a Fuzzy Cognitive Map (FCM) of factors affecting the rate of adoption of zero tillage in wheat in the rice-wheat system in northern India.

State/Concept	*Abbreviation used in FCM*	*Initial Activation*
Phalaris minor	Pminor	0.80
IPU-tolerant *P. minor*	rPminor	0.40
Rate coefficient of adoption	r	1.00
Number of adopters	A	0.23
Cost of Fuel	Fuelcost	0.6
New herbicides	Newherb	0.2
Diversification	Diversif	0.1
Government intervention	Interven	1.00 (0.00)[1]
Value of rice-wheat crops	Cropval	0.5
Cost of fertilizer	Ureacost	0.6
Profit	Profit	0.5
Ability to invest in new methods	Invest	0.3
Low interest rates	Lowint	0.3
Aggregation	Aggreg	0.5 (0.00, 0.25, 1.00)[1]
Cost of adopting zero tillage	ZTcosts	0.7
Mass-media promotion of zero tillage	Massmed	0.95
Lack of familiarity with zero tillage	Nofamili	0.77

Table 6.2 (cont.) Initial levels of activation in a Fuzzy Cognitive Map (FCM) of factors affecting the rate of adoption of zero tillage in wheat in the rice-wheat system in northern India.

Belief in need for tillage	Needtill	0.80`
Risk aversion to adoption	Toorisky	0.80

[1] Alternative initial values used in different projections are shown in parentheses

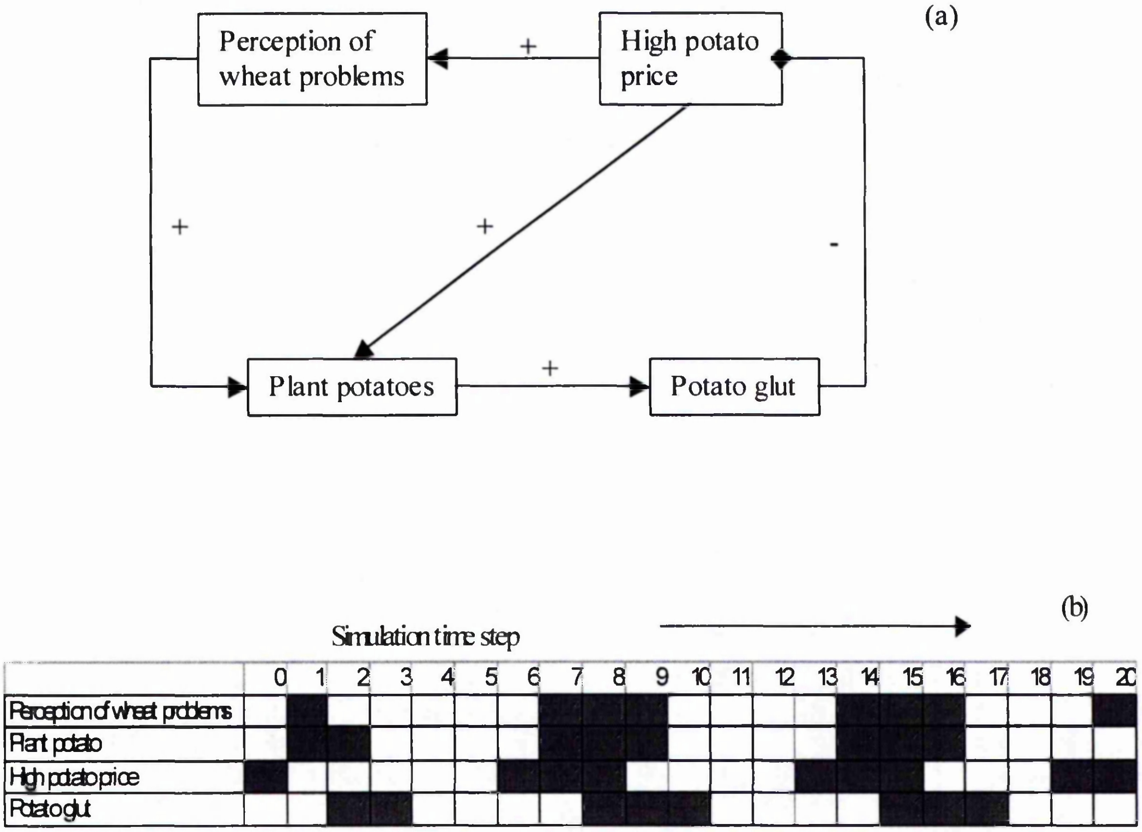


Figure 6.1 A simple example of capturing expert opinion in a fuzzy cognitive map (FCM). (a) Causal statements linking concepts (boxes) are shown as arrows. The direction of causation is indicated by the shape of arrowhead (?, increase), (♦, decrease) and by, respectively, + and – signs. (b) The projected dynamics of the FCM shown in (a) as a Markov process after translation of the FCM into a projection matrix. Shaded squares indicate presence of the corresponding state in the time step of the projection, open squares indicate absence of the concept in a time step. The sequence is initiated by high potato prices, but no other active concepts.

The effects of aggregation on the rate of adoption were included in the FCM as shown in Figure 6.2. To examine the dynamic nature of parameter *r* without aggregation, the causal connections between aggregation and other states were set to 0. This is analogous to the assumption of homogenous mixing in the farmer population. The FCM was also used to examine the predicted dynamics of the system with different initial levels of aggregation corresponding to the situations described above, with and without the effect of government intervention. Intervention was removed from the projections by setting its activation level to zero. The FCM analyses were carried out using the Fuzzy Thought Analyser (FTA, version 1.03 for Windows™, Fuzzy Systems Engineering, Poway, CA, USA). Adaptations to the diffusion model resulting from the observed dynamic nature of the *r* parameter are described in the results section.

Table 6.3 Causal statements linking states associated with the rate of uptake of zero tillage in the rice-wheat system of northern India.

Statement no.	*Statement*	*Weight*
1.	Adoption of zero tillage reduces *Phalaris minor* infestation	-0.60
2.	Use of new herbicides reduces *P. minor* infestation	-0.75
3.	Presence of *P. minor* results IPU-tolerant *P. minor*	1.0
4.	Adoption of zero-tillage reduces IPU-tolerant *P. minor*	-0.60
5.	Use of new herbicides reduces IPU-tolerant *P. minor*	-0.75
6.	Presence of *P. minor* increases attractiveness of zero tillage*	0.6
7.	Presence of IPU-tolerant *P. minor* strongly increases attractiveness of zero tillage	1.00
8.	High fuel prices strongly increase increases the attractiveness of zero tillage	1.00
9.	Diversification reduces the attractiveness of zero tillage	-0.60
10.	Ability to invest increases the rate of adoption	0.95
11.	High costs of zero-tillage machinery reduce attractiveness of zero tillage	-0.75
12.	Lack of familiarity with the technique reduces the attractiveness of zero tillage	-0.60
13.	Belief in the need for tillage reduces attractiveness of zero tillage	-0.75
14.	Risk averse attitudes reduce the attractiveness of zero tillage	-0.75
15.	A positive rate coefficient leads to an increase in adopters	1.00
16.	Intervention generally increases fuel costs	0.60
17.	Increase in crop value (rice-wheat) leads to increase in use of new herbicides	0.90
18.	Occurrence of IPU-tolerant *P. minor* leads to use of new herbicides	0.75
19.	Occurrence of *P. minor* stimulates diversification in cropping system	0.45
20.	Occurrence of IPU-tolerant *P. minor* stimulates diversification in cropping system	0.75
21.	Increase in crop value (rice-wheat) decreases diversification	-0.90
22.	Intervention generally increases crop value (rice-wheat)	0.90
23.	Intervention generally decreases fertilizer costs	-0.75
24.	High fuel costs reduce profitability	-0.75
25.	High crop values (rice-wheat) increase profitability	1.00
26.	High fertilizer prices decrease profitability	-0.80
27.	Profitability stimulates investment	0.90
28.	Low interest rates stimulate investment	0.95
29.	Intervention reduces interest rates for farmers' loans	0.50
30.	Increase in the number of adopters reduces aggregation among adopters	-1.00
31.	Increase in the number of adopters reduces costs of adoption of zero tillage	-0.90
32.	Intervention supports the use of mass media promotion of innovations	0.70
33.	Increase in the number of adopters leads to decrease in lack of familiarity of zero tillage among farmers	-0.75
34.	Aggregation among adopters maintains a lack of familiarity of zero tillage among adopters	0.80

Table 6.3 (cont.) Causal statements linking states associated with the rate of uptake of zero tillage in the rice-wheat system of northern India.

35.	Mass media promotion reduces lack of familiarity of zero tillage among adopters	-0.60
36.	Increase in the number of adopters reduces belief in the need for tillage	-0.75
37.	Aggregation among adopters maintains a belief in the need for tillage	0.80
38.	Lack of familiarity with zero tillage maintains a belief in the need for tillage	0.95
39.	Aggregation among adopters leads to maintenance of a risk averse attitude to adoption of zero tillage	0.80
40.	Lack of familiarity with zero tillage leads to maintenance of a risk averse attitude to adoption of zero tillage	0.90

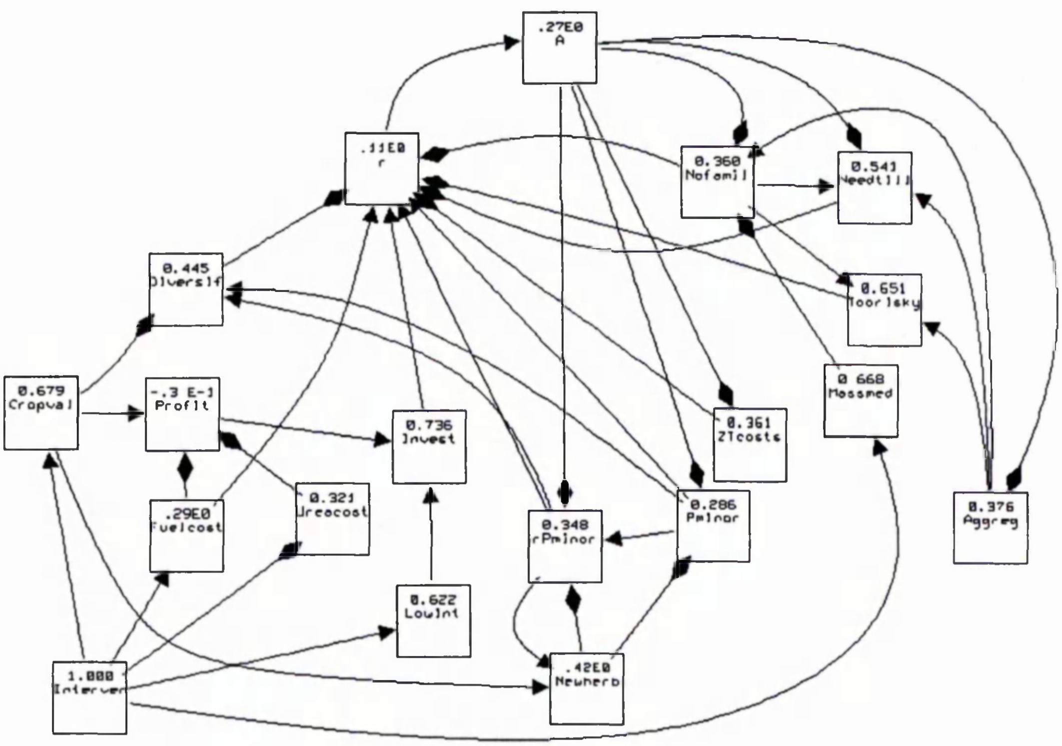


Figure 6.2 A fuzzy cognitive map of the rice-wheat system in northern India with particular attention to concepts which might affect the rate of adoption of zero tillage. The identities of the concepts are given in Table 6.2, together with their initial values. Causal statements are indicated by the arrows joining concepts as either (►) increase, or (♦) decrease and are listed in Table 6.3.

.3 Results

.3.1 *Effects of the initial level of aggregation on the innovation uptake*

Figure 6.3 shows the adoption curves for the four different initial levels of aggregation [Figure 6.3a] and the rate of adoption against time [Figure 6.3b]. It can be seen that an increasing level of aggregation among adopters leads to an increase in the time required to reach the final fraction of adopters and in the maximum rate of adoption during the adoption process. With the value of $r = 0.38$, the time required to reach 80% adoption in situation 1, the observed aggregation level, is delayed by 3.3 years as a result of aggregation compared with a situation in which there is random mixing of adopters and non-adopters. The relative increase in time compared with random mixing of adopters and non-adopters was 43%. Increasing the aggregation level by 50% (situation 4) compared with the field-based situation would extend the time required to reach 80% adoption by another 11 years (relative increase compared with random mixing: 207%).

Aggregation (LIP) as a function of the adoption fraction over time (equation 6.9) is shown in Figure 6.4. It can be seen that a 50% increase in the initial level of aggregation as compared with the observed value results in the pattern of adopters remaining aggregated (LIP>1) until close to the end of the adoption process. Analysis of equation 6.9 showed that a value of LIP(A) = 1.0 was obtained after 21 years starting from a position with 50% more aggregation than the observed value. For the field-based level of aggregation, the model predicted that the homogenous mixing of adopters and non-adopters would occur after 10 years.

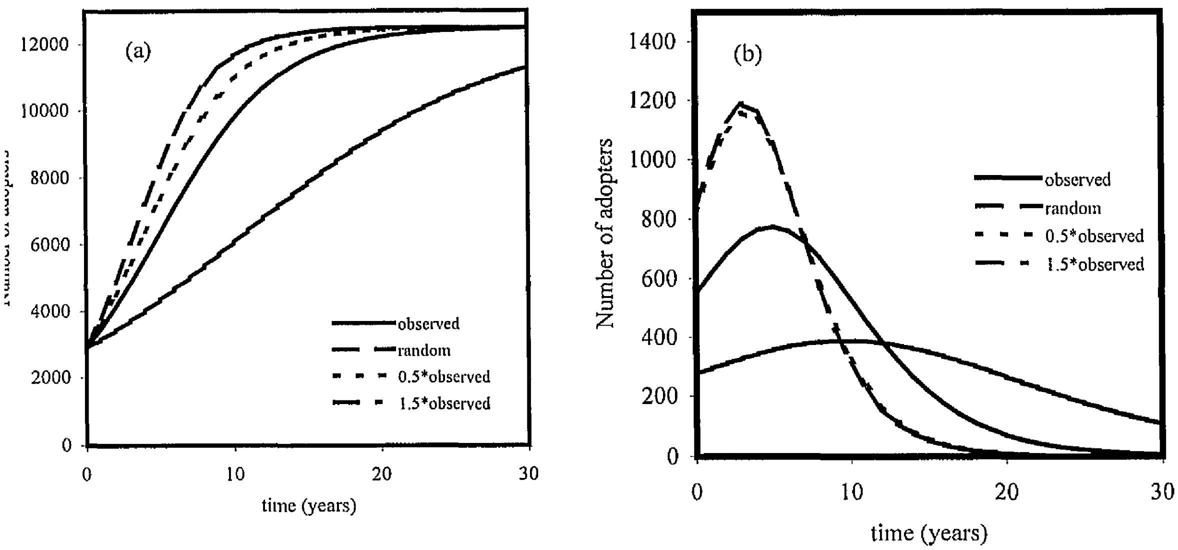


Figure 6.3 Predicted adoption curves (a) and corresponding rates of adoption (b) over time for the adoption of zero tillage in wheat in the northern Indian rice-wheat system. The dynamics of adoption are described by a modified logistic curve which accounts for non-homogenous mixing of adopters and non-adopters.

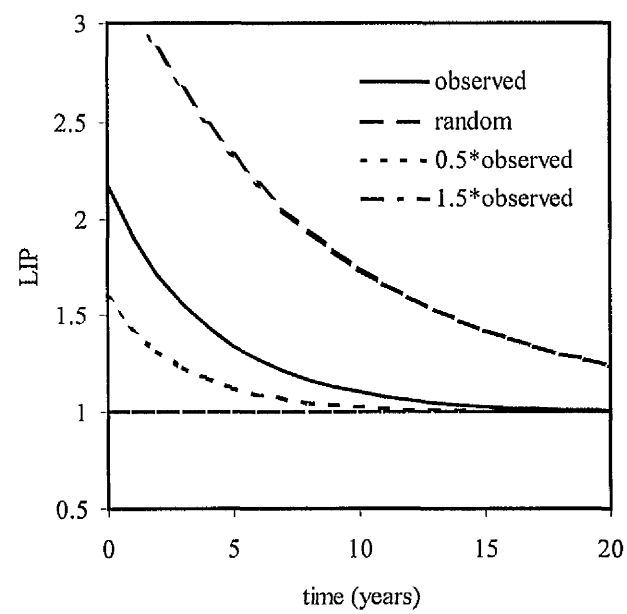


Figure 6.4 The behaviour of the predicted level of aggregation in the adopting population over time, for different assumptions about the observed level of aggregation at a single time point early in the adoption process.

.3.2 *Cognitive map dynamics*

Examination of the dynamics of the system suggested that a fixed attractor would be reached in a relatively short time. Overall, seriousness of the *P. minor* was predicted to decrease, but herbicide resistant *P. minor* was predicted to increase. Concurrent with the period of increase in resistant *P. minor*, farm income was predicted to fall, before showing a recovery to approximately its initial value. These predictions of the behaviour of the system broadly agree with its observed behaviour over the last eight to ten years. The input of state intervention *via* fuel and fertilizer prices and by supporting mass media information on zero tillage, was found to make little difference to the eventual level of adoption of zero tillage, but did lead to a slightly higher level of profitability in the system.

The rate coefficient, r, was found to reach a stable value within a few cycles of the FCM, irrespective of the presence of Government intervention, or the initial level of aggregation among adopters, although the final value of the parameter did depend on the presence of Government intervention in the system. The stable value of r was 10.5% higher in the case where intervention affected other states, compared with the case where no intervention was present [Figure 6.5].

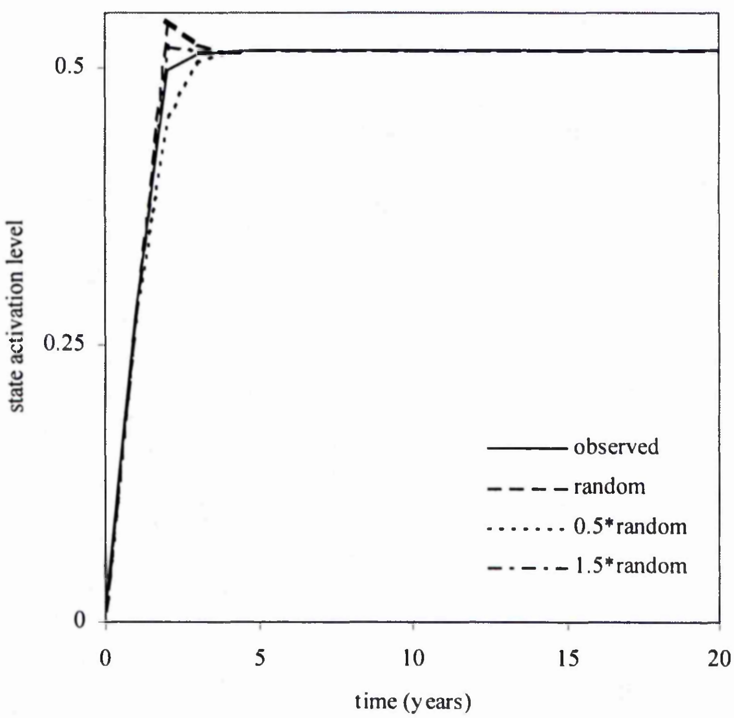


Figure 6.5 The projected behaviour of the rate parameter, *r*, in the fuzzy cognitive map shown in Figure 6.2 under different assumptions about the initial level of aggregation among adopters and the presence of government intervention in the economics of the cropping system.

.4 Discussion

In their discussion of the relative merits of phenomenological versus individual-based diffusion models Mahanjan, *et al.* [1990] noted that "...*all potential adopters do not have the same probability of adopting the product in a given time period.*" Individual-based models such as those proposed by Chaterjee & Eliashberg [1990] attempt to address this issue by modelling the processes of decision/adoption at an individual level. Although such approaches can give accurate fitting of adoption curves to observed adoption data, they require information on the behaviour of individual adopters which may not be easy to collect. The approach reported here is an attempt to find a compromise between the individual-based approach and the original Bass diffusion model. Specifically, the model uses information which can be collected, by direct observation, on the aggregation of the innovation within the adopting population to estimate an additional shape parameter for the diffusion model. The parameter *LIP* [Lloyd, 1967], based on the ecological concept of patchiness, specifically accounts for the way in which physical or social grouping within the adopting population might delay the adoption of an innovation by making the probability of adoption non-constant over those yet to adopt.

The proposed model has properties which make it useful for the context in which it was developed. First, it is known that, in common with other groups of adopters, farmers are more likely to adopt an innovation when either they can try it out before committing to it, or they can observe someone else trying it [Rogers, 1995]. This effect has already been observed with the adoption of zero tillage in India [Singh & Panday, 2002]. Clearly, the opportunities for non-adopters to observe adopters trying a new method are reduced in circumstances where adopter and non-adopters do not mix homogeneously in the population. Caste, religion and wealth all act as sources of aggregation within Indian villages and may lead to non-homogenous exchange of information about, or access to, technological innovations [Jodhka, 1998]. Second, detailed information on the adoption/decision process of adopters, a prerequisite for constructing a micro-level model and information which may be difficult to collect in a development context, is not required for the model presented here. Third the model is well-suited to situations in which the population of adopters consists of distinct social groups (*e.g.* villages) since the aggregation parameter is estimated simply from the mean and variance of the number of adopters per group (*i.e.* per village in the current context). Since such social structuring is a common feature of peasant agricultural systems, the current model may provide a basis for improved forecasting of technology adoption in development studies compared standard diffusion models.

Mahanjan *et al.* [1990] discussed the difficulties in obtaining parameter values for diffusion models in advance of the diffusion process reaching an advanced stage. In principle, the model presented here may not be as severely affected in this respect by lack of data as other diffusion models. First, the model's basic structure is that of the logistic equation in which the inflection point occurs at the mid-point in time of the diffusion process. This may make it possible to estimate the rate parameter, r, from a relatively short time series of data. Deviations from a symmetrical adoption curve arise in the current model as a result of the time-varying function of aggregation in the adopting population. Thus, although the rate parameter might be estimated as if the diffusion curve were symmetrical about its inflection point, the actual curve may be asymmetrical. Furthermore, the time-varying parameter (LIP) which affects the shape of the curve may be estimated from a single observation period, as illustrated above, provided reasonable estimates can be made of the number of potential adopters in each group, and the total number of potential adopters in the population.

Irrespective of whether parameter estimation for the proposed model proves to be easier than for other diffusion models or not, the principle use of the model is likely to be strategic rather than tactical in any case. That is, in common with other relatively simple models of complex processes [May, 1973], the main use is likely to be in understanding how the dynamics of the process might change in response to changes in a few key parameters. In such analyses, the interest is often in qualitative changes in the predicted behaviour of the system in response to changes in parameter values rather than in precise numerical analysis of particular fits of the model to data. The analysis of the model clearly indicated that extension efforts to reduce the aggregation of adopters would result in increased adoption rates.

In the current context, we considered it justifiable to focus attention on a diffusion model that accounted for diffusion as a result of 'internal' pressure only, rather than by both "internal" and "external" pressure. This decision was justified partly by the results of Sultan *et al.* [1990] who found that the coefficient of internal adoption pressure was an order of magnitude higher than that for external influence in a meta-analysis of 15 adoption studies. It was also based on the personal observation that a majority of Haryana farmers have been exposed to the concept of zero tillage through mass media coverage, but only those who have had direct experience of the method have actually adopted it.

The use of cognitive mapping allowed an examination of the overall context within which adoption of zero tillage is taking place in northern India. The cognitive maps generated projections of changes within the system, which are in agreement with observed data. For example, a gradual replacement of normal *P. minor* with IPU-resistant *P. minor*. A period of decrease in farm income associated with the increase in IPU-resistant *P. minor* followed by a period of recovery in farm income [Malik, 2001]. Given the qualitative agreement between the projections from the FCM and the observed behaviour of the system, it was of interest to examine the dynamics predicted for the rate parameter, r in the diffusion model.

The FCM projection suggested that the rate parameter would quickly increase to a stable value. The diffusion model given in equation 6.10 can be extended to include a variable expressing the diffusion coefficient (r in equation 6.10) rather than constant rate parameter. A possible parameterisation for such a model is given in equation 6.11.

$$\frac{dA}{dt} = \left(b \cdot \left(1 - e^{-a \cdot \frac{A}{N}}\right)\right) \cdot A \cdot \left[1 - \left(1 + \frac{LIP_{\left(\frac{A}{N}\right)} - 1}{LIP_{\max\left(\frac{A}{N}\right)} - 1} \cdot \left(\frac{N}{A} - 1\right)\right) \cdot \frac{A}{N}\right] \qquad 6.11$$

The new rate parameter in equation 6.11 is expressed as a function of the fraction of adopters (*A*/*N*). The new parameter, b, is the upper limit to which r tends, while a is a rate parameter which determines the time taken for r to reach its stable value. Numerical integration of equation 6.11 with values for a and b selected to mimic the projections from the FCM analysis varied little from the analysis based on equation 6.10, with constant r. Generally, if the rate parameter reaches a constant value early in the diffusion process, results from equation 6.11 are not likely to differ greatly from those for equation 6.10 and it is not clear that worthwhile benefits in explanatory power will be gained from the additional burden of further parameter estimation.

However, bearing the above reservations in mind, the combination of FCM analysis and a suitably parameterised diffusion model represents a useful set of analytical tools for the examination of technology diffusion in development studies.

CHAPTER 7: GENERAL DISCUSSION

'.1 Ecology and biology of *Phalaris minor*

The field studies of the biology and ecology of *Phalaris minor*, combined with an exploratory modelling study [Chapter 2, 3 & 4], have enhanced our understanding of the lifecycle of *P. minor* in the rice-wheat system and the mechanism by which various management practices affect the population dynamics of the weed. The collected data sets were occasionally fragmentary because of poor research and logistic facilities at HAU. However, replications of the experiments showed consistent patterns in the behaviour of the weed and a number of entirely new pieces of information on the biology of *P. minor* have been generated in this project. Consequently, the studies have assisted in setting priorities for further research and farmer extension on *P. minor* control on the Indo-Gangetic plains.

Studies of the longevity of *P. minor* seeds under various soil conditions showed that seed half-life time is usually limited to less than one year, but seed longevity may be prolonged when seeds are deeply buried under anaerobic circumstances. This result explains why alternative winter crops, that prevent *P. minor* seed shed, have a strong impact on *P. minor* seedling emergence in the subsequent year. Haryana farmers estimate a 90% reduction in *P. minor* seedling population size after a season with an alternative winter crop. This reduction can be explained solely by the short half-life time of *P. minor* seeds. On the other hand, long-lasting efforts will be required to eradicate *P. minor* from a field, as small quantities of seeds may survive in the soil for several years. Given the short longevity of *P. minor* seeds under field conditions, it is unlikely that the reduced seedling emergence rate of *P. minor* after direct drilling of wheat seed, as compared with conventionally sown wheat [Section 3.3.2], results in a long-term accumulation of seeds in the soil.

The study of the effects of tillage techniques on the vertical movement of beads through the soil profile indicated that, in a millet-wheat rotation, mouldboard ploughing before wheat sowing moves a larger fraction of *P. minor* seeds below 10cm under the soil surface than conventional ploughing using local machinery. As *P. minor* seeds are unable to emerge when buried below 10cm and seed longevity is often less than one year, mouldboard ploughing may assist in curbing weed populations. In rice-wheat rotations, the puddling operations associated with the rice cultivation are a major factor determining the relative vertical distribution of seeds through the soil profile. The present studies failed to provide consistent information on bead movement in the rice-wheat system, as puddling operations dispersed the beads over a large area and the bead recovery rate after puddling was low. This problem may be overcome by monitoring natural seed populations in heavily infested fields for several years. It would be interesting to study the effects of various soil cultivation practices during the rice cultivation on the relative distribution of *P. minor* seeds, including the effect of various water levels during puddling and the effect of different soil cultivation methods required for transplanted and direct-seeded rice. Such studies are especially relevant in the light of anticipated changes in soil cultivation methods in rice [Section 1.3.5] and the importance of *P. minor* seed longevity for its entire population dynamics [Section 4.3.3].

Straw burning studies showed that wheat straw burning in April or May could kill many recently shed *P. minor* seeds lying on the surface, but for commercial reasons, Haryana farmers rarely burn wheat straw. Rice straw burning in October or November, on the other hand, has little effect on the survival chances of *P. minor* seeds, because, at the time of burning, most seeds are covered with soil and protected from strong heat. In the literature, rice straw burning has been associated with increased *P. minor* seedling emergence [Kumar *et al.*, 2002; Singh *et al.*, 1999b], which could be related to the improved environment for seed germination after burning rather than a direct stimulatory effect of burning on seed germinability. As straw burning has been related to negative side effects, such as air pollution, reduced soil organic matter contents and enhanced *P. minor* seedling emergence [Brar *et al.*, 1995], it may be advisable to incorporate rice straw into the soil in conventionally tilled fields.

Straw incorporation is impossible in zero tillage systems. After combine harvesting of rice, loose straw remains on the soil surface and, if it is not removed or burned before wheat drilling, loose rice straw may retard early growth of directly drilled wheat. Given the rising labour costs for manual harvesting of rice, combine harvesting of rice is likely to grow in popularity, stressing the need to find appropriate methods to handle loose rice straw before direct drilling of wheat. Baling of rice straw would ease its removal and facilitate its transport and storage. Baled straw could serve as raw industrial material or as livestock feed after ammonium treatment. The economic feasibility of straw baling is presently limited by the high costs of foreign straw balers, while locally produced balers are not available yet. Research to adapt baling equipment to the environmental and socio-economic conditions prevailing at the Indo-Gangetic plains is presently going on at Pantnagar Agricultural University (Uttar Pradesh) [Thakur, 2002].

Soil seedbank sampling, conducted as part of the lifecycle studies [Chapter 3], revealed no systematic difference in *P. minor* seedbank composition or relative vertical distribution of seeds throughout the soil profile between fields under conventional and zero tillage. This was not a surprising result, as the experiments only lasted for one year at each location and did not aim to study the long-term effects of conventional and zero tillage on soil seedbank composition. While no systematic difference in soil seedbank composition between the tillage systems was observed, seedling emergence rates were consistently higher in fields under conventional tillage during first and second flush of weed emergence. This suggests that the variation in emergence rate between the tillage systems must be attributed to factors, such as variation in soil physical and chemical properties and differences in seed dormancy status as a result from light and mechanical stimulation during ploughing.

Soil compaction and crust formation in fields under zero tillage may play an important role in preventing *P. minor* seedling emergence. Wheat seedling emergence was not hindered by crust formation in fields under zero tillage, as wheat germinated in rows where the soil was rent apart by the seed drill. The hypothesis that crust formation hindered *P. minor* emergence was supported by the observation that most *P. minor* seedlings in fields under zero tillage emerged within the wheat rows. Additional data recordings on spatial emergence of *P. minor* seedlings in fields under conventional and zero tillage would be useful to test this hypothesis. Wheat sowing under relatively dry soil conditions enhances crust formation and may therefore assist in curbing weed emergence. Given the importance to reduce reliance on herbicides for *P. minor* control, the interaction effects between soil moisture levels during sowing, and wheat and *P. minor* seedling emergence in zero tillage systems should be studied in an experimental trial.

The lifecycle studies provided indications that IPU-resistant *P. minor* biotypes are cross-resistant against the herbicide fenoxaprop-P-ethyl. As poor control rates of fenoxaprop-P-ethyl were observed at two locations in two different years, poor herbicide performance was unlikely to be related to faulty herbicide application techniques or extreme environmental conditions. Recently, other studies have also reported signs of *P. minor* resistance against fenoxaprop in Haryana and Punjab [Yadav *et al.*, 2002a; Bhullar *et al.*, 2002; Brar, 2002]. Emerging multiple-resistance among *P. minor* biotypes is obviously a major concern and stresses the need to reduce reliance on herbicides for weed control.

Differences in *P. minor* emergence rate between fields under conventional and zero tillage was not observed to affect weed densities at final harvest. Irrespective of the tillage system, without effective weed control later in the season, wheat yield losses due to *P. minor* pressure were significant at final harvest. This suggests that, when the alternative herbicides fail to control *P. minor* in the future because of multiple-resistance development, zero tillage alone will not save Haryana farmers from crop failure.

The model of *P. minor* population dynamics [Chapter 4] confirmed specific results from the seedbank dynamics and lifecycle studies. The model facilitated the exploration of alternative weed management strategies, which could not be tested in field experiments because of time and financial constraints. Despite the limited availability of reliable input parameters and the descriptive nature of the model, it produced realistic outputs, which were in line with independent field observations from various sites in Haryana.

Indications, provided by the lifecycle studies, that large seed losses occur between seed shed and seedling emergence in the subsequent growing season were supported by the model. It suggested that 75 to 85% of the newly shed seeds are lost by the beginning of the following growing season due to seed predation, decomposition and seed removal during wheat harvest. Manipulation of *P. minor* seed loss at this stage offers new possibilities to improve *P. minor* control and should be studied in more detail. For example, after manual harvesting of wheat, bundles of wheat with *P. minor* plants, harvested along with wheat, are usually stored in the field for several days up to several weeks, allowing *P. minor* plants to continue shedding its seeds. Direct removal of wheat bundles with *P. minor* plants after harvesting may result in increased *P. minor* seed losses. It is unknown to what extend *P. minor* seeds, harvested during combine harvesting of wheat, return to the field with the chaff and straw. Given the size differences between wheat and *P. minor* seeds, it is well possible that a large fraction of the *P. minor* seeds returns to the field. Development of seed catching machinery can be effective in retaining these seeds, which would require collaboration between weed scientists and local agricultural engineers.

A sensitivity analysis revealed that the model of the population dynamics of *P. minor* is highly sensitive to changes in the value of parameters related to soil seedbank dynamics, especially to changes in seed longevity. This supports the suggestion made above to continue research to the effects of various wheat and rice management practices on *P. minor* seed longevity. In addition, simulated *P. minor* population dynamics were highly sensitive to changes in herbicide efficacy rate, supporting the presently ongoing project to improve herbicide application accuracy among farmers in northern India and Nepal [Bellinder *et al.*, 2002].

The model suggested that the advantages of reduced emergence rates in fields under zero tillage increases with reduced herbicide inputs, irrespective of the actual *P. minor* density. This may be a general feature of agro-ecosystems, as also Vencill & Banks [1994] observed that increasing weed management inputs diminishes differences between tillage systems. In addition, model simulations indicated that alternating wheat with other winter crops without the use of herbicides might be a suitable *P. minor* control strategy, but only in combination with the use of zero tillage techniques in wheat. The only field information available on the effect of crop diversification on *P. minor* pressure origins from farmer surveys, as presented in Chapter 5. Experimental trials to the effects of crop diversification on *P. minor* population dynamics have never been reported, probably because of time constraints. However, such trials would be very helpful in verifying the model's predictions and in gaining insight in the possibilities to reduce herbicide reliance through crop diversification.

While the risk of *P. minor* developing cross-resistance against one of the newly introduced herbicides has been recognised by many scientists [Brar, 2002; Brar *et al.*, 2002; Yadav *et al.*, 2002a; Malik *et al.*, 1998], no studies have addressed the topic of evolutionary adaptation of *P. minor* to new cropping rotations, soil conditions or to cultural or mechanical control measures. In Section 2.3.1, it was mentioned that the seed longevity of seeds buried at Hisar might have been reduced because of poor adaptation of Karnal biotypes to Hisar soil conditions. The present trend of *P. minor* to extend its distribution area towards drier and sandier areas of southern Haryana, where cotton-wheat, millet-wheat and fallow-wheat rotations prevail, suggests that *P. minor* is capable of adapting to new soil conditions and other cropping rotations than rice-wheat. *P. minor* may also show evolutionary adaptation to new cultivation methods such as zero tillage. Even though there is abundant evidence that weeds are capable of adaptation to biological, mechanical and cultural control measures, attempts to predict this adaptive ability are generally rare, as it requires specific, quantitative information on the weed's variability in genetic traits and the selection factors in the field [Jordan & Jannink, 1997]. Predicting the capability of *P. minor* to adapt to zero tillage systems is presently not a realistic aim, as collection of the required information would be very laborious. However, a first assessment of the ability of *P. minor* biotypes to adapt to local soil conditions would be useful in indicating whether the present geographic trend of the *P. minor* distribution area should be attributed to changing field management practices or to evolutionary adaptation of the weed to new soil conditions and cropping rotations.

2 Socio-economic context of *Phalaris minor* epidemic

The socio-economic audit distinguished two types of stratification among the farmer population of Haryana [Chapter 5]. Farmers could be classified based on geographic location and on socio-economic position. The geographic distinction was mainly the result of regional differences in climatic and soil conditions and consequently, differences in cropping pattern, farm management, resistance development and farm economics. The socio-economic stratification was based on a range of interrelated factors, such as scale of farming, intensity of mechanisation, farm profitability and access to information on farming. Characteristics of the strata were not absolute, but a general pattern could be observed. A group of profitable farms was identified with large landholdings (>4ha), high levels of mechanisation, often with additional income besides farming and frequently visited by extension officers and company representatives. These farmers considered *P. minor* as a major threat for the profitability of their farm and were successful in controlling *P. minor* by spending relatively large sums of money on effective herbicides. They favoured technical solutions, such as herbicides, to control *P. minor*. A group of small farmers (2-4ha) was distinguished of which many were unable or unwilling to spend sufficient money on effective herbicides. High *P. minor* densities put their farm profitability under pressure. A group of very small farmers (<2ha) was discerned who managed to control *P. minor* better than the small farmers using crop rotation and manual weeding, but their farm profitability was low, probably due to the small scale of farming. Small farmers usually had no other sources of income besides farming.

In Haryana, there is still a strong need to reach a more sustainable production system using new production technologies. Predicting the usefulness and adoption rate of new, more sustainable agricultural technologies requires knowledge of the existing composition of the farming community. The survey showed that the Haryana farmer community cannot be treated as a homogeneous group of farmers that only differ in the degree of innovativeness. Therefore, the traditional diffusion model explaining how innovations spread through a population [Röling, 1988] may not be applicable for the Haryana farming community. Whereas farmers with a strong socio-economic position successfully adopted alternative herbicides in the areas infested with IPU-resistant *P. minor* biotypes, farmers with a poor socio-economic position failed to adopt alternative herbicides, despite the high rate of return on investments in herbicides at the end of the growing season. 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 on farming and differences in psychological characteristics.

On the evidence of the farmers' estimates of the frequency with which extension agents visited them, it was concluded that government as well as company extension agents in Haryana preferred to work with farmers with a strong socio-economic position, aggravating the situation of unequal adoption among the farming community. Farmers with a poor socio-economic position may prefer low-input methods of controlling *P. minor*, such as diversification of the cropping system and wheat varieties with better weed suppressing abilities. These means of controlling *P. minor* have received little attention from agricultural scientists and extension officers. Consequently, little research and development progress has been made on better exploitation of these techniques over the last decade. The focus on relatively advanced weed control methods indicates, in addition, that research and development priorities are designed to suit the needs of resource-rich farmers. An obvious consequence of this top-down approach to modernise agriculture by targeting resource-rich farmers is that the information, technology and income gap between resource-rich and resource-poor farmers will widen, which may ultimately lead to the expulsion of rural people out of farming and consolidation of the scale of farming.

The interaction between the structure of the farming community and the rate of adoption of zero-tillage was examined using a population dynamic modelling approach [Chapter 6]. A new innovation diffusion model was developed, based on ecological theory of the effect of population crowding on growth rate. The model indicated that the types of stratification of the farmer population identified in the system audit could have significant effects on the rate of uptake of innovations such as zero tillage. The development of the model was aided by the use of cognitive mapping [Kosko, 1993] to summarise the interactions among the various factors, which might determine the adoption rate of technological innovations. Although the work carried out in this project was preliminary, the results suggested that the combination of cognitive mapping and dynamic modelling might have wide application for studying technology adoption in complex agricultural systems.

3 Final conclusions

As no single measure is likely to solve the *P. minor* epidemic, an integrated approach is required to improve the sustainability of wheat production in Haryana [Malik *et al.*, 1998]. Even though many farmers presently obtain reasonable *P. minor* control rates using foliar applied herbicides, first signs of the development of cross-resistance against the newly introduced herbicides have appeared. Development of cross-resistance can be retarded using herbicide rotations, but farmers' ignorance about the mechanism by which weeds develop resistance and farmers' dependency on local middlemen who usually provide only one type of herbicides [Section 5.3.5] impede wide-scale adoption of herbicide rotations so strongly that herbicide rotation may be an infeasible target. Faulty herbicide spraying techniques, cost saving exercises using herbicide rates below the recommended rate and farmers' inability to recognise early signs of cross-resistance may further accelerate the development of cross-resistance.

Wide-scale adoption of reduced tillage techniques will assist in curbing *P. minor* pressure by reducing the weed's emergence rate, but application of zero tillage techniques alone is insufficient to control *P. minor* and the possibility of evolutionary adaptation of *P. minor* to the soil conditions prevailing in fields under zero tillage should not be excluded. Likewise, adoption of wheat varieties with increased weed suppressing abilities may assist in controlling *P. minor*, but the cultivation of such varieties alone will not provide satisfactorily weed control. Crop diversification should be assigned a central place in the development of an integrated weed management strategy. Alternative winter crops, which are presently cultivated in Haryana, prevent *P. minor* seed shed and are, because of the short longevity of *P. minor* seeds in the soil, highly effective in reducing the weed's population size. As soil conditions that prevail in paddy rice benefit *P. minor* seed longevity, a change in cultivation practices of the summer crop may also affect the weed's population demography. Diversification of the summer crop may also assist in controlling *P. minor* by changing the soil conditions, keeping in mind however that there are signs that *P. minor* is capable of adapting to other soil conditions than those prevailing in rice-wheat systems.

The topic of diversifying the rice-wheat system in Haryana has been frequently debated [Dreze, 2001; Reddy, 2000]. Crop diversification is impeded by the important role Haryana fulfils as a provider of food grains to other states of India, which are not self-sufficient in the production of food grains. This role is supported by the government's policy of providing minimum support prices and storage facilities to farmers growing rice and wheat. At present however, India has a large grain surplus of around 50m tons. Given the rising costs for grain procurement, storage of the mounting buffer stocks and the forced uneconomical export of Indian grains for world market prices, the pressure on the Indian government to abandon the system of minimum support prices is increasing. Moreover, as a member of the World Trade Organisation, the Indian government is also subject to pressure from abroad to cut down its agricultural subsidies. While the grain storages are overloaded, malnutrition has been far from eliminated in India. Still, around 20% of the rural people in India suffers from malnutrition and the poor nutritional status is considered as one of the main impediments for further socio-economic development in India [World Bank, 1998]. Present grain surpluses in India appear to be the result of a distribution and poverty problem rather than a problem of overproduction of food grains.

The debate about the topic of diversification of the farming system has highlighted the demand for participatory land use planning. An exploratory land use analysis study of Haryana by Agarwal *et al.* [2001] concluded that, with the projected availability of resources in year 2010, opportunities exist to diversify cropping pattern and increase the income from farming, while maintaining Haryana's share in food grain production for the growing population of India. The study recommended a decrease in the area of cotton and pearl millet and an increase in the area of mustard and chickpea. To maximise income from farming, a larger area in the south of Haryana should be left fallow during the summer season. Production targets for the year 2010 could only be reached by greater adoption of efficient and capital-intensive technologies on a large proportion of the land. Another land use analysis study of Haryana [Kumar *et al.*, 2001] suggested that there is a considerable potential to withdraw agricultural land from production without affecting basic food production and income from farming at the state level, given a greater adoption rate of higher technology. Both studies concluded there is space for crop diversification and extensification of the agriculture in certain parts of Haryana, but only with the simultaneous adoption of more efficient, capital-intensive technologies. Further productivity growth should come from increased farmer knowledge, better timing of application of inputs, better ploughing techniques and not from an increased use of inputs.

Adoption of higher farming technologies on a greater proportion of the land in Haryana is affected by the present progressive farmer approach for the introduction of agricultural innovations. As mentioned before, the present top-down approach may ultimately lead to consolidation of the farming system, because of the increasing technology and poverty gap between resource-rich and resource-poor farmers, which may force many small farmers out of business. Consolidation of the scale of farming will facilitate the adoption of more intensive technologies. However, roughly half the working population of Haryana in directly engaged in farming and 41% of these farmers owns less than 1ha of land [Anonymous, 1996]. Off-farm employment opportunities for the vast number of small farmers who are threatened to go out of business are limited. Moreover, the cities' poor infrastructures have not been designed to carry the mass movement of people from rural areas to cities. Therefore, small farmers are likely to remain a significant feature of the rural economy of Haryana for long time to come, even when considerable efforts are undertaken to enhance off-farm employment opportunities.

To stimulate the adoption of higher farming technologies on a larger proportion of the land in Haryana, while maintaining sufficient employment opportunities within farming, higher technologies should be made available for small farms to increase their resource-use efficiency. Zero tillage techniques and improved spraying techniques are examples of recently introduced technologies that are also suitable to increase the resource-use efficiency at small farms. However, the present tendency of agricultural scientists and extension agents in Haryana to address the needs of resource-rich farmers does not enhance the adoption of higher technologies at small farms. Special research and development programmes that specifically target technology problems of small farmers may greatly benefit *P. minor* control, as well as the overall performance and sustainability of the agriculture in Haryana.

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APPENDIX I: SOIL PHYSICAL AND CHEMICAL CHARACTERISTICS OF THE EXPERIMENTAL FIELDS AT PIRTHALA AND NARNAUND

The soil analyses were carried out by the SAC Central Analytical Laboratory during June 2002. Both soils were characterised as being of low Nitrogen status. The salinity level of the Narnuand sample was considered to be of a level which might lead to crop damage.

Soil Chemical Analysis

	Pirthala	Narnaund
Texture	Silty clay loam	Silty clay loam
% loss on ignition	3.8 (low)[1]	4.6 (low)
pH (Water)	8.1	8.6
Available P (mg l^{-1})	14 (1)[2]	19 (2)
Available K (mg l^{-1})	119 (1)	143 (2)
Extractable Mg (mg l^{-1})	365 (6)	670 (7)
Salinity (μS cm^{-1})	2350 (1)	3150 (6)

[1]Term in parentheses refers to classification according to standardised UK soil analyses
[2]Term in parentheses refers to the following sacle: 0=very low; 1=low; 2=moderate; 3=high; 4-7=extremely high

Soil Particle Size Analysis

	Pirthala	Narnaund
Particle type		
SAND		
* Very course (>1mm)	0.02	0.06
* Coarse (0.5-1mm)	0.04	0.19
* Medium (0.25-0.5mm)	0.21	0.25
* Fine (0.125-0.25mm)	0.88	1.36
* Very fine (0.063-0.125mm)	17.00	16.79
* Total Sand	18.14	18.65
* SILT	60.18	54.63
* CLAY	21.68	26.72
STONE (% by mass)		
2-6.35 mm	0.0	0.0
>6.35 mm	0.0	0.3

* As a percentage of total <2mm mineral fraction by mass

APPENDIX II: PROGRAM STRUCTURE OF THE POPULATION MODEL

```
DEFINE_CALL HERBIC (INTEGER_INPUT,INPUT,INPUT_ARRAY,INPUT_ARRAY,...
      INPUT_ARRAY,INPUT_ARRAY,INPUT_ARRAY,INPUT_ARRAY,...
      OUTPUT_ARRAY,OUTPUT_ARRAY)

ARRAY APD(1:NL),BIOMP(1:NL),EMR(1:NL),EMRC(1:NL),EMRZ(1:NL)
ARRAY HEFF(1:NL),HEFF0(1:NL),HEFF1(1:NL), HEFF2(1:NL)
ARRAY MID(1:NL),NES(1:NL),PHAS(1:NL)
ARRAY SURV(1:NL),SURV0(1:NL),SURV1(1:NL),SURV2(1:NL)


TITLE Phalaris minor population flux model, in competition with wheat

ARRAY_SIZE NL=3

DYNAMIC

*** 1. Soil seedbank

NSS   = INTGRL(NSSI,NSSR)
NSSR  = -NEST - MORT + SPROD2
MORT  = MORTR*(NSS-NEST)
NSSB  = NSS*FSB
NSSA  = NSS*(1.-FSB)
FSB   = INSW (PLSWI,FSBZ,FSBC)
PLSWI = AFGEN(PLFUNC,TIME)


*** 2. Seedling emergence

NEST    = NES(1) + NES(2) + NES(3)
NES(1:NL) = EMR(1:NL) * NSSA
EMR(1:NL) = INSW (PLSWI, EMRZ(1:NL), EMRC(1:NL))


*** 3. Midseason plant density

MIDT = MID(1) + MID(2) + MID(3)
MID(1:2)  = PHAS(1:2)/(1.+((PHAS(1)+PHAS(2))/MIDMAX))   ;...
MID(3:NL) = NES(3:NL)
PHAS(1:NL)= NES(1:NL)*(1.-HEFF(1:NL))
HERB = AFGEN(HFUNC,TIME)

CALL HERBIC (NL,HERB,HEFF0,HEFF1,HEFF2,SURV0,SURV1,SURV2,HEFF,...
    SURV)


*** 4. Number of adult plants

APD(1:NL) = SURV(1:NL)*MID(1:NL)
BIOMT     = BIOMP(1)*APD(1)+BIOMP(2)*APD(2)+BIOMP(3)*APD(3)
APDT      = APD(1)+APD(2)+APD(3)
```

```
*** 5. Seed production

SPROD  = BIOMT*HI/SEEDW
SPROD2 = SSURV*SPROD


**************************************************************
*                        Model Parameters                    *

*  Section 1
INCON NSSI = 2000.
PARAM FSBZ = 0.125   ; FSBC= 0.23
PARAM MORTR= 0.9

FUNCTION PLFUNC = 0.,-1., 1.,-1., 2.,-1., 3.,-1., 4.,-1., 20.,-1.
* PLFUNC:  1.: conventional ploughing    -1.: zero-tillage

*  Section 2
PARAM EMRZ(1)= 0.12; EMRZ(2)=0.15; EMRZ(3:NL)=0.06
PARAM EMRC(1)= 0.22; EMRC(2)=0.18; EMRC(3:NL)=0.09

*  Section 3
MIDMAX = 300.
FUNCTION HFUNC = 0.,2., 1.,2., 20.,2.
* HFUNC    0.:no control   1.:IPU     2.:clodinafop/sulfosulfuron

PARAM HEFF0(1)=0.;   HEFF0(2)=0.;   HEFF0(3:NL)=0.
PARAM HEFF1(1)=0.1;  HEFF1(2)=0.3;  HEFF1(3:NL)=0.
PARAM HEFF2(1)=0.98; HEFF2(2)=0.95; HEFF2(3:NL)=0.
* HEFF0:no control  HEFF1:IPU   HEFF2:clodinafop/sulfosulfuron

*  Section 4
PARAM APDMAX = 200.
PARAM BIOMP(1)=5.14;  BIOMP(2)=3.716;  BIOMP(3:NL)=2.29
PARAM SURV0(1)=0.617; SURV0(2)=0.223; SURV0(3:NL)=0.1307
PARAM SURV1(1)=0.617; SURV1(2)=0.223; SURV1(3:NL)=0.1307
PARAM SURV2(1)=0.693; SURV2(2)=0.077; SURV2(3:NL)=0.0594

*  Section 5
PARAM HI=0.273;   SEEDW=0.00178
PARAM SSURV=0.2

**************************************************************


TERMINAL

*** 6. Run Control

TIMER STTIME=0.; FINTIM=30.;DELT=1.;PRDEL=1.
TRANSLATION_GENERAL DRIVER='EUDRIV'; TRACE=4
PRINT APD,APDT,NSS,SPROD2,SPROD,NES,MID,NEST
```

```
END

*** 7. Reruns

PARAM HEFF2(1)=0.98; HEFF2(2)=0.95; HEFF2(3:NL)=0.
FUNCTION PLFUNC = 0.,1.,15.,1.
END


FUNCTION PLFUNC = 0.,-1., 15.,-1.
PARAM HEFF2(1)=0.9; HEFF2(2)=0.9; HEFF2(3:NL)=0.
END

FUNCTION PLFUNC = 0.,1., 15.,1.
PARAM HEFF2(1)=0.9; HEFF2(2)=0.9; HEFF2(3:NL)=0.
END


FUNCTION PLFUNC = 0.,-1., 15.,-1.
PARAM HEFF2(1)=0.8; HEFF2(2)=0.8; HEFF2(3:NL)=0.
END

FUNCTION PLFUNC = 0.,1., 15.,1.
PARAM HEFF2(1)=0.8; HEFF2(2)=0.8; HEFF2(3:NL)=0.
END


FUNCTION PLFUNC = 0.,-1., 15.,-1.
PARAM HEFF2(1)=0.98; HEFF2(2)=0.95; HEFF2(3:NL)=0.
FUNCTION HFUNC= 0.,2., 5.,2., 6.,0., 7.,2., 10.,2., 11.,0., 12.,2.,...
   13.,2., 16.,2., 17.,0., 18.,2., 22.,2., 23.,0., 24.,2., 27.,2.,...
   28.,0., 29.,2., 31.,2.
END

FUNCTION PLFUNC = 0.,1., 15.,1.
FUNCTION HFUNC= 0.,2., 12.,2., 13.,0., 14.,2., 15.,2., 25.,2.,...
  26.,0., 27.,2., 28.,2.
END

STOP
```

```
      SUBROUTINE HERBIC (NL,HERB,HEFF0,HEFF1,HEFF2,SURV0,SURV1,SURV2,
     $   HEFFS,SURVS)

      IMPLICIT REAL (A-Z)
      INTEGER NL,IS
      REAL HERB,HEFF0(NL),HEFF1(NL),HEFF2(NL),HEFFS(NL)
      REAL SURV0(NL),SURV1(NL),SURV2(NL),SURVS(NL)
      SAVE

      DO 10 IS=1,NL
```

```
      IF (HERB.EQ.0) THEN
        HEFFS(IS)=HEFF0(IS)
        SURVS(IS)=SURV0(IS)
      ELSE
      ENDIF

      IF (HERB.EQ.1) THEN
          HEFFS(IS)=HEFF1(IS)
          SURVS(IS)=SURV1(IS)
      ELSE
      ENDIF

      IF (HERB.EQ.2) THEN
           HEFFS(IS)=HEFF2(IS)
           SURVS(IS)=SURV2(IS)
      ELSE
      ENDIF

   10 CONTINUE

      RETURN
      END

ENDJOB
```

APPENDIX III: DEFINITION OF THE ABBREVIATIONS USED IN THE SIMULATION PROGRAM

APD(1:NL)	Adult plant density for flush 1 to NL [plants m^{-2}]
APDT	Total adult plant density [plants m^{-2}]
BIOMP(1:NL)	Individual plant biomass for flush 1 to NL [g $plant^{-1}$]
BIOMT	Total plant biomass [g m^{-2}]
EMR(1:NL)	Actual seedling emergence **rate** for flush 1 to NL [seedlings $seed^{-1}$]
EMRC(1:NL)	Seedling emergence rate after conventional tillage for flush 1 to NL [seedlings $seed^{-1}$]
EMRZ(1:NL)	Seedling emergence rate after zero tillage for flush 1 to NL [seedlings $seed^{-1}$]
FSB	Actual fraction of seeds of the entire seedbank below 10cm depth
FSBC	Fraction of seeds of the entire seedbank below 10cm depth after conventional tillage
FSBZ	Fraction of seeds of the entire seedbank below 10cm depth after zero tillage
HEFF(1:NL)	Actual herbicide efficacy for flush 1 to NL [plants $seedling^{-1}$]
HEFF0(1:NL)	Herbicide efficacy under herbicide-free conditions for flush 1 to NL [plants $seedling^{-1}$]
HEFF1(1:NL)	Herbicide efficacy after application of isoproturon for flush 1 to NL [plants $seedling^{-1}$]
HEFF2(1:NL)	Herbicide efficacy after application of clodinafop for flush 1 to NL [plants $seedling^{-1}$]
HERB	Herbicide number
HFUNC	Herbicide function, describes applied herbicide as a function of time
HI	Harvest index [g g^{-1}]
MID(1:NL)	Plant density at midseason for flush 1 to NL [plants m^{-2}]
MIDMAX	Maximum plant density for first and second flush together [plant m^{-2}]
MIDT	Total plant density at midseason [plants m^{-2}]
MORT	Soil seed mortality due to decomposition [seeds m^{-2}]
MORTR	Soil seed mortality rate
NES(1:NL)	Number of emerged seedlings for flush 1 to NL [seedlings m^{-2}]
NEST	Total number of emerged seedlings [seedlings m^{-2}]
NL	Array size (equals the number of flushes)
NSS	Soil seed density [seeds m^{-2}]
NSSA	Soil seed density above 10cm depth [seeds m^{-2}]
NSSB	Soil seed density below 10cm depth [seeds m^{-2}]
NSSI	Initial soil seed density [seeds m^{-2}]
PHAS	Plant density after herbicide spraying [plants m^{-2}]
PLFUNC	Plough function, describes applied ploughing techniques as a function of time
PLSWI	Plough switch
SEEDW	Weight of an individual seed [g $seed^{-1}$]
SPROD	Number of seeds on mother plant [seeds m^{-2}]
SPROD2	Inflow of fresh seeds in the soil seedbank [seeds m^{-2}]
SSURV	Seed survival rate

SURV(1:NL)	Actual survival rate of plants from midseason until final harvest for flush 1 to NL
SURV0(1:NL)	Survival rate of plants from midseason until final harvest for flush 1 to NL under herbicide-free conditions
SURV1(1:NL)	Survival rate of plants from midseason until final harvest for flush 1 to NL after application of isoproturon
SURV2(1:NL)	Survival rate of plants from midseason until final harvest for flush 1 to NL after application of clodinafop
TIME	Time passed since start of the simulation [y]

APPENDIX IV: FARMER QUESTIONNAIRE

DFID questionnaire for farmers in Haryana, 2000-2001

Interviewer's name:

Date:

1. Respondent and farm details

1.1 Farmer's name:

1.2 Village:

1.3 District:

1.4 No. of family members working on the farm

1.5 No. of hired labour during wheat cultivation

1.6 Size of landholding:

1.7 Landholding: possessed / rented

1.8 No. of tractors:

1.9 Machinery shared with other farmers? Yes / No

1.10 No. of cows and buffalo's:

1.11 Present *Phalaris* density in field (no./m^2):

1.12 Soil type:

Details wheat cultivation 2000/01

!.1 Crop rotations (April 2000 – April 2001):

:.2 Stubble management before sowing

Stubble size: 0-15 cm. / 15-30 cm. / >30 cm.

Stubbles: Burned / incorporated / other

2.3 Land preparation

Type of tillage: conventional / zero till / raised bed

No. of harrowing:

No. of planking:

No. of cultivator:

2.4 Seeding

Wheat variety:

Seed source: newly purchased seed / last year's harvest / exchange with other farmers

Seed sieved: yes / no

Type of sowing: conventional / direct drill / broadcast

Seed rate wheat:

Sowing date wheat:

2.5 Irrigation

Type of irrigation: canal / tube well

Time of first irrigation:

Total number of irrigation:

Did moisture stress occur?

2.6 Fertilisation

Urea DAP MOP Green manure

2.7 Chemical weed control

Name of herbicide:

Dose:

Time of application:

Costs (rupee/ha):

Type of nozzle

Efficiency (%):

Who applies herbicides: Farmers / Hired labour

2.8 Manual weed control

Period of hand weeding:

Who conducts weeding:

Number of man-days spent:

Costs:

2.9 Wheat harvest: manual / combiner

Manual harvest by: family members / hired labour

2.10 Weeds

Estimated wheat yield reduction as a result of *Phalaris*:

Other weeds besides *Phalaris*:

2.11 Profitability wheat

Wheat yield:

Costs wheat cultivation

Wheat seed:

Soil cultivation:

Electricity:

Herbicides:

Fertilisers:

Harvest:

Transport to market:

Details wheat cultivation 1999-2000

3.1 Crop rotation (April 99-April 00):

3.2 Type of tillage: conventional / zero till / raised bed

3.3 Chemical weed control

Name of herbicide:

Costs:

Efficiency:

3.4 Estimated wheat yield reduction as a result of Phalaris:

3.5 Wheat yield:

4. Farmer's perception

Please rank the following questions from one to five:

5 very bad

6 bad

7 moderate

8 good

9 very good

4.1 How do you judge the *Phalaris* problem compared to other weeds, pests and diseases in the wheat culture?

4.2 How severe is the *Phalaris* problem for the profitability of your farm in general?

4.3 How do you judge the financial situation of your farm compared to five years ago?

4.4 How do you judge the potential of new herbicides to combat *Phalaris*?

4.5 How do you judge the potential of new cultivation methods, like zero till or harrowing?

4.6 How do you judge the potential of new wheat cultivars with better weed suppressing abilities?

4.7 How do you judge the potential of hand-weeding?

4.8 How do you judge the potential of raising other crops than wheat in winter?

5 Other questions

5.1 Did you notice any signs of IPU resistance of *Phalaris* in your field? Yes / No / Not sure

5.2 If appropriate, how did you change your management after discovering isoproturon resistance?

5.3 Which herbicides other than isoproturon are you able to buy?

5.4 Did *Phalaris* densities in your fields increase or decrease recent years? Increase / Decrease

5.5 How many rupees are you able and willing to invest in relieving the *Phalaris* problem?
0-200 / 200-500 / 500-1000 / >1000

5.6 Are you able to raise other crops than wheat in winter? Yes / No
If yes, which crop(s)?

If not, what are the main constrains?

5.7 Do you discuss your farm management with other farmers? Yes / No

5.8 Do you take advice on wheat growing from

Other farmers?	Yes / No
Advisory officers from government?	Yes / No
Advisory officers from university	Yes / No
Company representatives?	Yes / No
Radio / TV / Newspaper	Yes / No

5.9 Does landless labour harvest *Phalaris* in your fields?

If yes, do you support this practice?

5.10 Is there anything you would like to add to this questionnaire?