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DEMANIR, a Simulation Model of Insecticide Resistance Development and Management

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Abstract We have written a simulation model to predict the effects of various pesticide uses and insect management regimes on the frequency of susceptible and resistant insects using the modelling program VENSIM®. The model, DEMANIR (**DE**velopment and **MAN**agement of **I**nsecticide **R**esistance), is based on the saw-toothed grain beetle, *Oryzaephilus surinamensis* (L.). DEMANIR enables simulation of various insecticide use patterns and management strategies of grain protectants (insecticide) to prolong their effective life. DEMANIR allows for the density dependent effects on reproductive rate and migration, with a Poisson-distributed random variable added to the migration term; differing reproductive potential on various types of grain; effects of farm hygiene; variation in fitness levels between susceptible and resistant beetles. It is possible to model the use of different chemicals and chemical use patterns in combination with variation in protectant efficacy. Protectant efficacy includes the criteria: time since treatment; insecticide resistance level and protectant application efficiency. The program incorporates default settings (scenario) but these can be varied for each simulation run. Each run simulates two years, with a harvest in each year and various clean-up (hygiene) and insecticide treatment strategies. Initial simulations indicate that in the absence of organophosphate (OP) use, the proportion of resistant insects declines, but does not reach zero. OP use reverses that trend, but unexpectedly does not eliminate all susceptibles. Untreated grain provided a "refugia" for susceptible insects which influences resistance development. The maintenance of such "refugia" is discussed in terms of overall insecticide use and grain protection.

1. INTRODUCTION

Pesticide resistance management is essential as more than 477 arthropod species have developed resistance and conservatively costs $16 b annually (Georghiou 1986). Pesticide resistance in arthropods is occurring with an ever increasing frequency, in both numbers of species and pesticides affected (Georghiou 1986). The phenomenon of insecticide resistance is well illustrated in stored product insects on farms (Herron 1990), and preliminary models of stored product pests have been developed (Muggleton 1986; Sinclair and Alder 1985). Pesticide resistance management is an option often considered by entomologists, but requires a considerable knowledge of the insect pest's biology and population dynamics to effectively implement (Roush and Daly 1990). Roush and Daly (1990) detail 10 techniques for manipulating selection pressure in integrated resistance management strategies. One important management approach listed is the preservation of refuges (refugia) for susceptibles to breed.

The stored product pest, saw-toothed grain beetle, *Oryzaephilus surinamensis* (OS), was chosen as a good insect to model. This beetle is at present resistant to all the organophosphate (OP) grain protectants (insecticides applied to grain) used against it, with only the Insect Growth Regulators (IGRs) providing effective control. Protectant resistance to newer materials, started in 1983 with resistance to fenitrothion followed by pirimiphos-methyl and chlorpyrifos-methyl resistance by 1986 (Collins *et al.* 1987, Herron 1990). Consequently, the biology and population dynamics of this insect are different to the one (*Sitophilus oryzae* L.)) used by Sinclair and Alder (1985). Considerable information is available on the general biology and relative survival of resistant and susceptible OS genotypes (Sinha 1971, Muggleton 1986) and the results of laboratory grain bioassays to a range of resistant and susceptible genotypes are also available (Collins 1985).

The model is based on farm management practices observed at Grong Grong during a large farm survey (Herron 1990). We have written the simulation model using the modelling program Vensim® Ver. 1.61 (Ventana 1994) to predict the effect of pesticide use, farm hygiene and insect management regimes on the frequency of resistant OS.

We report the structure, detailed equations and assumptions of the model; discusses the results of simulation in relation to the Grong Grong survey and speculate on future implications for resistance management.

2. MATERIALS AND METHODS

2.1 Biological Information

Population parameters for OS development on a range of grain types were obtained from Sinha (1971). He provided information on OS population increase when reared on a range of varieties of soft and hard wheats, barley and oats. Sinha (1971) found OS fed soft wheat multiplied 7-8 fold; 5-6 fold on hard wheats; 10-11 fold on barley and 10-13 fold on oats. These factors were used to provide the fecundity values for OS on the differing grain types. Muggleton (1986) determined the relative fitness of malathion resistant OS to be 0.8 compared to that of susceptible OS. We have used that fitness value for OP resistant OS in our model.

2.2 Efficacy of Insecticide Treatments

Collins *et al.* (1987) showed resistant OS could readily survive in protectant treated grain. Protectants investigated by Collins *et al.* (1987) included fenitrothion, pirimiphos-methyl, chlorpyrifos-methyl and the insect growth regulator methoprene. Results of those grain bioassays, in terms of adult mortality and establishment of infestation, were used to provide an estimate of the effectiveness of the various insecticides for susceptible and resistant OS.

Azamethiphos will control fenitrothion resistant insects, but fenitrothion will not (Wallbank pers. comm.) In the model we assume azamethiphos excludes 80% of all OS, but fenitrothion is only active against susceptible OS.

2.3 Model Structure

The DEMANIR model includes three grain storages, holding wheat, barley and oats, and assumes two harvests over two years. The time interval is 0.125 years (ca. 6 weeks, or one OS generation). The model also includes a grain spill, containing mixed and damaged grain, which is replaced after each harvest. OS can migrate into and out of each grain storage; migration rates are density dependent and are influenced by the type of insecticide surface spray applied to the grain storage walls prior to filling (if any). A random Poisson variable is added to storage migration.

Insect multiplication within each grain storage is dependent on grain type, protectant treatment and resistance level. If fumigation with phosphine occurs all insects are eliminated. The only protectant fully effective against OP resistant insects is methoprene. Most variables are subscripted for grain type and insect resistance status; and incorporate differences in OS reproductive potential and insecticide effectiveness. Farm hygiene is incorporated as a cleanup of grain spills and reduced insect migration. The frequency of resistant OS is determined for each individual grain storage and for the overall farm population. The relative effectiveness of each protectant is reflected in the mortality of resistant OS.

2.4 Model variables

The "dynamic variable" drives the model and that is the presence of adult insects. The initial insect infestation (both susceptible and resistant) is specified for each grain storage (Startads).

There is a total of 35 variables and two sets of subscripts in DEMANIR.

Variables are divisible in three groups which are: Population variables (eg Adult, Adult Deaths, Eggs, Larvae, Pupae, Fecundity, Fecund Females); Insecticides and their Effectiveness (eg Fumigant, Pre Harvest SS (storage wall surface spray), Pre Harvest T (grain protectant), Post Harvest SS, Post Harvest T, Res Level); physical variables (eg Time, Time Step, Final Time, Storage Volume, Cleanup, Harvest). Some of the variables are additionally influenced by time, harvest, cleanup, pesticide treatment and storage volume.

The subscripts are: grain type; wheat, oats, barley, mixed; susceptibility to insecticides; susceptible, resistant. This is a simplification of a complex genetic system (Roush and Daly 1990), but it does enable real differences in insecticide effectiveness to be included.

2.5 Model equations

There is insufficient space to describe all equations, so only the main equations are detailed. Vensim® arranges the equations in appropriate order.

1. Eq (1) is the dynamic model variable:

   Adult [substrate, susc status] = INTEG ((Pupae [substrate, susc status] * survival [substrate, susc status] * Cleanup [substrate] - (Adult deaths [substrate, susc status] + Migra Out [substrate, susc status]) * Cleanup [substrate] + Migra In [substrate, susc status]), startads [substrate, susc status])

2. Eq (2) introduces the influence of fumigation:

   Fumigate [substrate] = IF THEN ELSE (Time = 0.375 : OR : Time = 1.375, Fumig Effic [substrate], 1)

3. Eq (3) describes the interaction between the spraying of grain storage walls with insecticide prior to filling and insect migration into the storage:

   Migra In [substrate, resistant] = IF THEN ELSE (storage volume [substrate] <= 0.2, 0, SUM (Migra Out [substrate!, susc status!]) * AvRes * 0.005 * Surface Sp [substrate]) + Random Poisson (N)
   Susceptible N = 3; Resistant N = 1.

4. Eq (4) ensures that a minimum of one fecund female is required to establish an infestation, otherwise the value is 0:

   Fecund Females [substrate, susc status] = IF THEN ELSE (Adult [substrate, susc status] < 1.99, 0, Adult [substrate, susc status] * Gender * Cleanup [substrate] * Fumigate [substrate].

5. Eq (5) calculates the influence of cleanup at specific times. Individual values can be set for each grain storage and spill:

Cleanup [substrate] = IF THEN ELSE (Time = 0.625 : OR : Time = 1.625, Factor [substrate], 1).

6. Eq (6) determines which insecticide protectant treatment is applied to the grain in storage. Pre Harvest indicates grain in storage at the start of a simulation and after the second harvest. Post Harvest indicates the grain stored from the first harvest which is retained until the next harvest. Separate treatments can be set for Pre and Post, as well as for each storage and susceptibility level:

   Spray Effect [substrate, susc status] = IF THEN ELSE (Time < 0.625 : OR : Time > 1.625, Pre HVT [substrate, susc status], Post HVT [substrate, susc status]).

7. Eq (7) allocates the volume of stored grain in litres. We assume 1 L of wheat is approximately equivalent to 0.8 kg. Additionally, the effect of having a grain spill can be included, as well as changing the relative amounts of various types of grain:

   Storage Volume [substrate] = IF THEN ELSE (Time < 0.75 : OR : Time > = 1.75, Pre Harvest [substrate], Post Harvest [substrate]).

2.6 Model Simulations

2.6.1 The default settings were:

- empty wheat and barley storage walls sprayed with fenitrothion prior to filling;
- wheat initially containing no OS and grain protected with fenitrothion;
- barley initially with some insects and grain protected with fenitrothion (susceptible and resistant OS in a 5:1 ratio respectively);
- oats initially with some insects and no grain protectant or storage wall treatment (susceptible and resistant OS in a 5:1 ratio respectively);
- an untreated grain spill with unrestricted OS movement into and out of the grain spill (susceptible and resistant OS in a 2:1 ratio respectively).

2.6.2 Simulation runs were:

- first simulation: Default settings as above;
- second simulation: All default settings except azamethiphos replaces fenitrothion as the spray on grain storage walls;
- third simulation: Azamethiphos again replaces fenitrothion as the spray for the grain storage walls, however, the survival of susceptible OS in treated barley was increased (simulating pockets of untreated grain);
- fourth simulation: All default settings except oats was treated with fenitrothion after the first harvest;
- fifth simulation: All default settings except azamethiphos again replaces fenitrothion as a grain storage wall treatment and oats is again treated with fenitrothion after the first harvest;
- sixth simulation: All default settings except the oats were again treated with fenitrothion after the first harvest (as simulation 4) and fenitrothion used as oats storage wall treatment.
- seventh simulation: All default settings except azamethiphos is used to treat empty grain storage walls prior to filling and no grain spills assumed;
- eighth simulation: All default settings except empty grain storage walls are not sprayed at all prior to filling.

2.7 Model Output

Vensim® writes values for each variable at specific time intervals (time step); in this case at 0.125 years (ca. 6 weeks). The data can be graphed or downloaded to a spreadsheet. Variables of specific interest include Resistance level, the frequency of resistant OS in each storage and for the farm; Fecund females, susceptible and resistant, for each storage and both Migration In and Migration Out which provide an indication of the mobility of resistant OS within the farm. This is reflected in the level of infestation that develops in initially uninfested storages.

3. RESULTS AND DISCUSSION

For comparative purposes we have selected: simulation 1 and 3 (Fig. 1a); simulation 1 and 4 (Fig. 1b); simulation 1, 2 and 8 (Fig. 1c); simulation 1, 3 and 7 (Fig. 1d); simulation 4 (Fig. 2a); simulation 1 (Fig. 2b); simulation 5 and 6 (Fig. 2c); and simulation 7 and 8 (Fig. 2d). The three main model outputs used were AVRES per farm; Reslevel (proportion resistant OS) for each grain type and storage; and Fecund Females.

Variation in DEMANIR parameter values caused major differences in final resistance frequencies in OS populations. Using default value settings caused overall farm resistance frequency to increase from 0.167 to 0.352 (Fig. 1c). When survival of susceptible OS in fenitrothion treated barley (simulation run 3) was increased from 0.1 to 0.25, the final average OS resistance frequency was marginally reduced to 0.324 (Fig. 1d). That was achieved by the average OS resistance frequency in the barley decreasing from 0.907 to 0.826 (Fig. 1a).

Treating the wheat basically prevented OS infestation. At the end of the default run (simulation 1) there was only one resistant OS in the wheat and no OS if azamethiphos was used as the grain storage surface spray (simulation 2). However, if no surface spray was used, 1.5 OS were

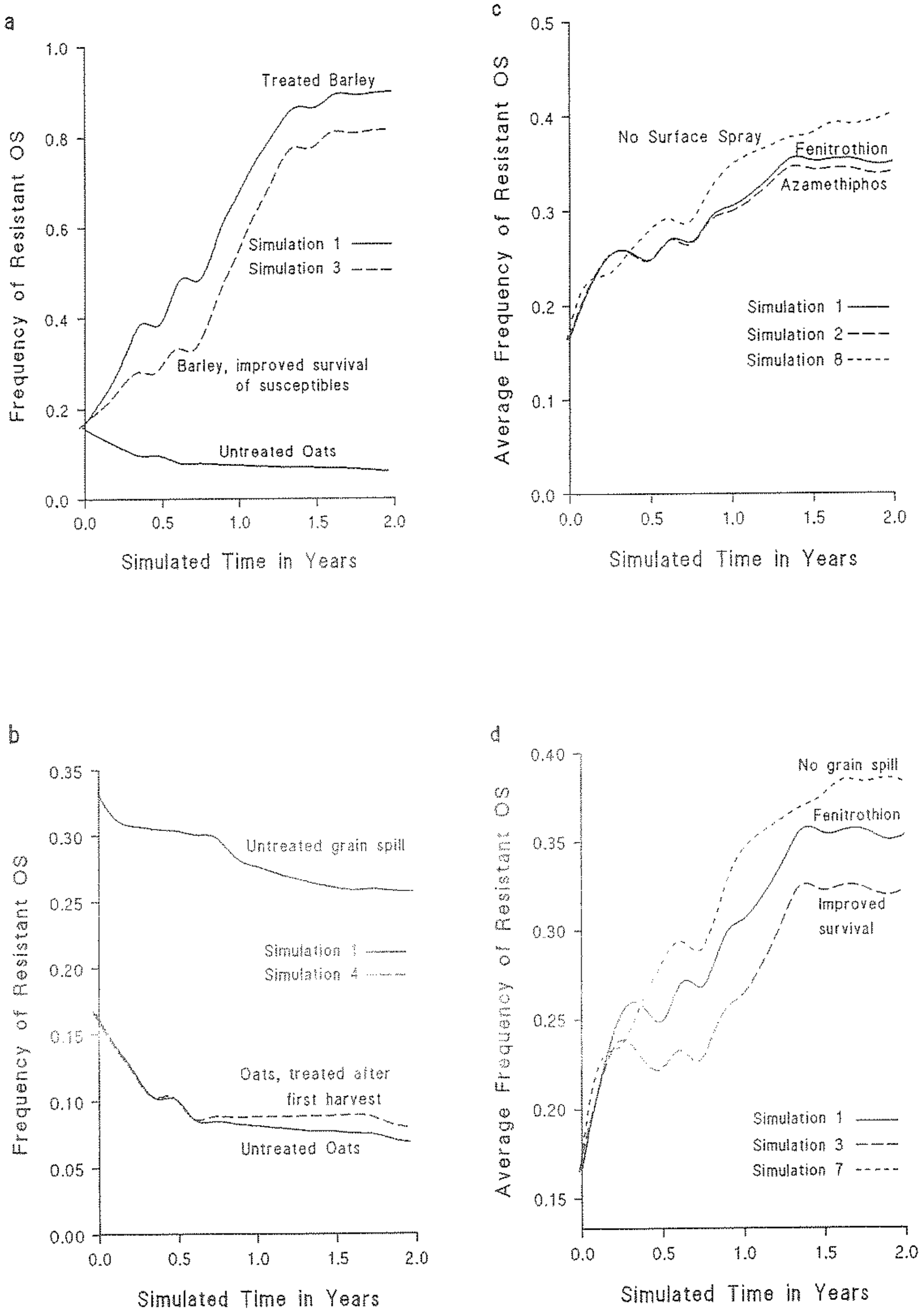

Figure 1. Effects of parameter settings on the frequency of resistant *Oryzaephilus surinamensis:* (a) grain protectant use, (b)(d) removal of survival of susceptibles, (c) surface sprays.

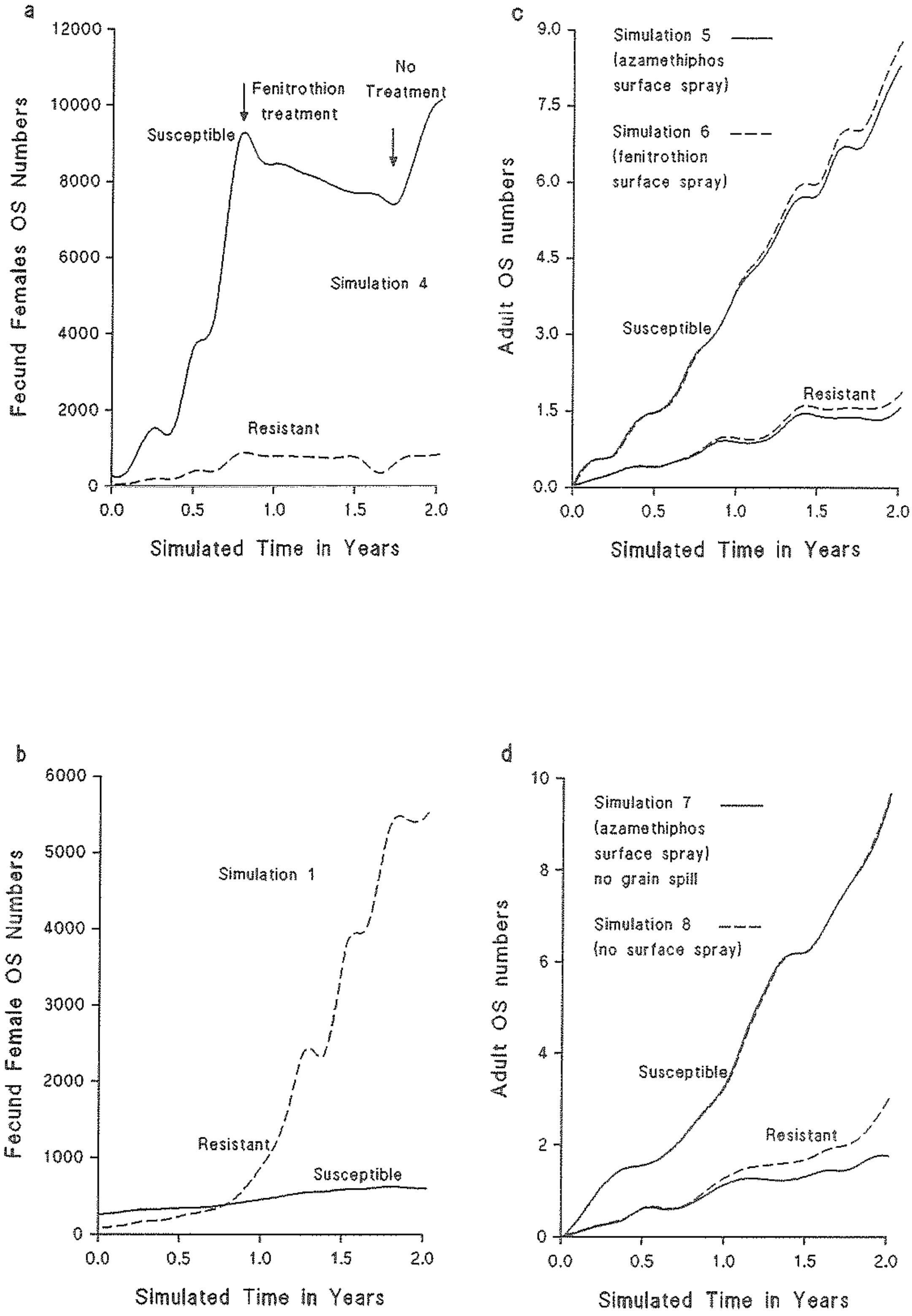

Figure 2. Effects of parameter settings on numbers of resistant and susceptible *Oryzaephilus surinamensis* in: (a) treated oats (b) treated barley (c)(d) wheat.

present (simulation 8) (Fig. 2d). The effects of various surface spray treatments on populations of OS in wheat are given in Figs 2c,d. Azamethiphos reduced both susceptible and resistant OS (Fig. 2c). Resistance frequency increased rapidly in fenitrothion or pirimiphos-methyl treated barley, from 0.167 to 0.907 (Fig. 1a). However, resistance decreased in the untreated grain spill in the absence of insecticides, from 0.333 to 0.258 (Figs 1a,b).

No insecticide treatment, or treatment with an insecticide effective against resistant OS, resulted in a similar slow decline in resistance frequency (Fig. 1b). This was achieved by a much greater rate of increase in numbers of susceptible OS compared to resistant OS (Fig. 2a). Use of azamethiphos as a surface spray reduced the rate of infestation by resistant OS (Fig. 1c).

When resistant and susceptible OS were allowed to reproduce in treated grain, but the rate was less for susceptible, increasing from 250 to 560, compared to resistant increasing from 50 to 5490 (Fig. 2b). In the grain spill, the susceptibles increase from 10 to 55 whereas the resistant increase from 5 to 19.

The results from DEMANIR are broadly consistent with the results obtained from the grain farm survey (Herron 1990) and from Muggleton's (1986) general model. Herron (1990) found OS surviving in grain treated with either fenitrothion or pirimiphos-methyl. The surface spray azamethiphos was not reported as being used on any of the survey farms, although DEMANIR suggests it could be useful in restricting the spread of resistant OS. Muggleton (1986) assumed no migration in his general model, but we conclude it clearly influences spread of resistance.

The rapid increase in resistance frequency in grain treated with fenitrothion or pirimiphos-methyl was expected. We also anticipated the slow decline in untreated grain or grain treated with the IGR methoprene. This is consistent with Muggleton (1986). The influence of an untreated grain spill on reducing the overall frequency of resistance is interesting as it has clear implications on farm hygiene.

In DEMANIR's default settings there were two untreated storages (i.e. oats and the grain spill). Removing either of these increased the incidence of resistant OS (Fig. 1d). In the interests of hygiene grain spills should be removed, but some untreated grain storage is necessary to reduce the incidence of resistant OS. If all residues are treated, the resistance frequency increases (Fig. 1c) and absolute numbers also increase (Fig. 2a,b).

Azamethiphos shows activity against several resistant stored product pests (Wallbank 1982) and it seems to be effective in restricting movement of the insects (Figs 1c, 2c). Muggleton's (1986) general model allowed for a variable portion of the OS to avoid treatment. In DEMANIR the untreated OS are physically separated from the treated, but migration is possible. Reduction of migration by using a storage wall spray that does not discriminate between susceptible and resistant OS (azamethiphos, Wallbank 1982) acts to reduce the frequency of resistant OS (Figs 1c, 2c).

4. CONCLUSION

For the purpose of resistant management in on-farm grain storage we suggest, on the basis of the model DEMANIR, good hygiene combined with prophylactic use of effective grain storage wall sprays, grain protectant use on long term grain storage only and no protectant use on short term storage. This restricts long term damage to stored grain, while supplying refugia to aid resistance management.

5. References

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