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AN INDIVIDUAL-BASED TWO-LOCUS MODELLING OF PEST CONTROL IN A SPATIAL HETEROGENEOUS STORAGE FACILITY WITH PEST IMMIGRATION

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ABSTRACT

The grain industries world-wide are confronted with a severe problem of pest control. Computer simulation models can provide a relatively fast, safe and inexpensive way to weigh the merits of various management options for pest control. We constructed an individual-based two-locus stochastic model to investigate the impact of two important issues on controlling a very serious cosmopolitan pest of stored grain, lesser grain borer (*Rhyzopertha dominica*). One issue is the consistency of phosphine dose achieved within a spatially heterogeneous storage facility and the other is the immigration rate of the adult pest. To test how consistency of dose affects the pest infestation, we assumed that each beetle actually experiences a different dose to every other beetle. This is generated individually according to a power law distribution. These different doses represent various factors in the storage facility including varying amounts of phosphine circulation, physical and chemical reactions etc. We also considered different immigration rates. These represent the movement of pests from outside to inside a storage facility, the amount of grain hygiene used around the facility, and the degree of proper sealing of the facility, etc. Based on the available data, we use a two-locus model, with two alleles at each locus, giving nine possible genotypes in total. We set up the initial resistance allele frequencies for the beetles so that the equilibrium frequency for the strongly resistant genotype was 0.1. The simulation results showed that when the dose achieved within the silo is very inconsistent, there will always be a problem for population control, especially if immigration rate is high.

Key words: Individual-based, two-locus, pest control, lesser grain borer, phosphine dose consistency, immigration rate.

1. INTRODUCTION

The lesser grain borer, *Rhyzopertha dominica,* is a very destructive primary pest of stored grains. There is a world-wide need for the development of sustainable management strategies to avoid the evolution of resistance and to control pest infestation. Computer simulation models can provide a relatively fast, safe and inexpensive means to weigh the merits of various management options.

In this study we extend our individual-based two-locus model to include spatial variability in dose and immigration of adult insects. This enables us to address two main management questions:

- Q1: How does the consistency of dose achieved within the storage facility affect the evolution of resistance to phosphine and population numbers?
- Q2: What is the impact of immigration rate of adult beetles on the evolution of resistance to phosphine and population numbers?

2. METHODS

2.1. Overview of the model

The overall model dynamics for an individual are illustrated in Fig. 1. Our models run on a daily time step. A number of processes within the simulation are determined stochastically. Full details of the processes and simulation steps have been provided previously (Shi et al, 2012a, 2012b).

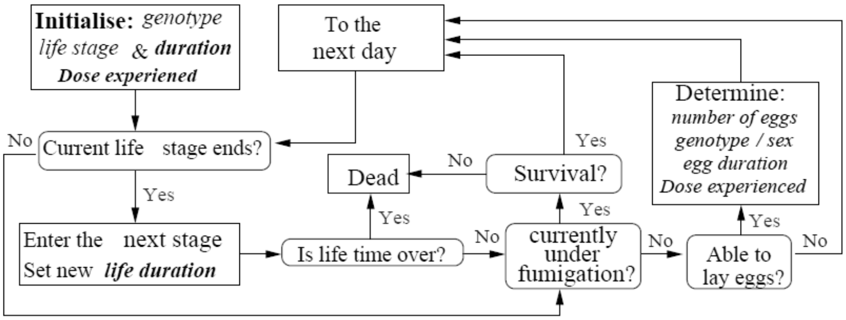

Fig. 1- The simulated dynamics for individual beetles at each daily time step during the simulation.

2.2. Two loci and nine genotypes

In our two-locus model, there are two possible alleles on each of two loci, meaning nine genotypes in total (Table 1, Shi and Renton, 2011).

2.3. Parameters

The model parameters take the same values as those in our previous papers (Shi *et al*, 2011, 2012a, 2012b; Shi and Renton, 2011). We set the number of starting female (a 1:1 sex ratio was assumed) beetles to be 100,000 (100K) and the initial frequencies for the nine genotypes are as follows:

$$\begin{array}{ccccccccc} ss & hs & rs & sh & hh & rh & sr & hr & rr \\ [0.21860, & 0.20219, & 0.04675, & 0.20219, & 0.18702, & 0.04325, & 0.04675, & 0.04325, & 0.01] \end{array} \qquad (1)$$

Table 1. The identifiers of nine genotypes (*ss*, *sh*, …, *rr*), in the two-locus model: *s* – homozygous ("homo") susceptible ("suscept"); *r* – homozygous resistant (resist); *h* – heterozygous

2nd gene	*s*	*h*	*r*
1st gene	homo suscept	heterozygous	homo resist
s homo suscept	***ss*** Both homo suscept	***sh*** 1st homo suscept & 2nd heterozygous	***sr*** 1st homo suscept & 2nd homo resist
h heterozygous	***hs*** 1st heterozygous & 2nd homo suscept	***hh*** Both heterozygous	***hr*** 1st heterozygous & 2nd homo resist
r homo resist	***rs*** 1st homo resist & 2nd homo suscept	***rh*** 1st homo resist & 2nd heterozygous	***rr*** Both homo resist

2.4. Addressing Q1 regarding the impact of dose consistency

In this study, the starting target fumigation dose is selected as $C_0 = 0.15$ mg/l for 14 days. The total survival rates for this treatment are 3.114×10^{-5} for *rr*, 3.341×10^{-12} for *rh* and $< 5.14\times10^{-29}$ for the other seven genotypes. However, each beetle actually experiences a different dose to every other beetle, due to spatial heterogeneity within the silo. To model this variability, the dose that each beetle is exposed to is generated individually according to a power law distribution defined by a parameter *k.* This parameter *k* depends on the maximum or nominal target dose ($d_{\max}$) and the median dose (d_{m}) in the following way:

$$k = \log(0.5)/\log(d_{\mathrm{m}}/d_{\max}) \tag{2}$$

We generate a uniformly distributed random number *p* for each individual and then the dose *d* experienced by the individual is yielded from:

$$d = d_{\max} p^{1/k} \tag{3}$$

This ensures that the expected median dose over many individuals is indeed d_{m}. We used three median doses ($d_{\mathrm{m}} = 0.14, 0.11, 0.08$ mg l^{-1}) to test how different amounts of variability in dose affects the evolution of resistance and population increase. These represent real factors in a spatially heterogeneous storage facility including varying PH_3 circulations, leakage of PH3 from silo, degree of physical and chemical reactions such as uptake or release of gas from or into grain (sorption-desorption) (Banks, 1989), and so on.

2.5. Addressing Q2 regarding the impact of immigration rate

Immigration was represented by simply adding a number of adult beetles into the population each day of the simulation. We considered four different immigration rates: 0 (no immigration), 20, 100 and 500 (adult beetles per day) respectively. The factors represented by these different rates include hygiene conditions, the degree of proper seal of the facility, and the movement of pests from dirty places outside to inside a storage facility.

2.6. Simulations

All (12) combinations of median doses (3 levels) and immigration numbers (4 levels) were simulated (Table 2).

Table 2. The short-hand identifiers for the 12 combinations of median doses and immigration rates considered in the study, including three cases without immigration and nine cases with immigration (Maximum dose = 0.15 mg l^{-1})

Median dose (mg l^{-1})	No immigration	With immigration (number of immigration per day)		
		20	100	500
0.14 (D14)	D14N0	D14N20	D14N100	D14N500
0.11 (D11)	D11N0	D11N20	D11N100	D11N500
0.08 (D08)	D08N0	D08N20	D08N100	D08N500

3. RESULTS

We ran all of the 12 simulations six times to check for stochastic variation, and found the results were very close to one another each time. The important patterns in the results for the 12 cases when the initial frequency of the *rr*: *f*(*rr*) = 0.01 are summarized in Table 3. These show that:

- In the four cases with a very consistent high dose (D14) population numbers are zero or close to zero.
- In the case with medium consistent dose (D11)
    - if the immigration is high (D11N500), population numbers are increasing
    - for other immigration rates or no immigration (D11N0, D11N20 and D11N100) population numbers are decreasing
    - In the four cases with a very inconsistent dose (D08), population numbers are all increasing.

There is an important transition point at the case D11N100 where the pattern changes from decreasing when the immigration rates are not more than 100 per day to increasing when the rate is higher than 100 per day.

On the other hand, the corresponding proportions of the *rr* beetles (Prrs) at the end of each of eight fumigations are as follows

- In the four cases with a very consistent high dose (D14) the *rr* proportions are zero or in a stable interval.
- In the case with medium consistent dose (D11)
    - if there is no immigration (D11N0) the *rr* proportions are increasing up to 100% and then decreasing down to zero.
    - if there are immigrations (D11N20, D11N100 and D11N500), the *rr* proportions are decreasing and then stable varying in a small interval.
- In the four cases with a very inconsistent dose (D08), the *rr* proportions are all increasing.

Table 3. Patterns of total (local minimal) population numbers (TPNs) and corresponding *rr* proportions (Prrs) at the end of fumigations listed. The following notation is used:

- ${}_{N1}\uparrow^{N2}$: TPNs or Prrs increasing over time with each fumigation from N1 up to N2
- ${}^{N1}\downarrow_{N2}$: TPNs or Prrs decreasing over time with each fumigation from N1 down to N2
- ~[N1, N2]: TPNs or Prrs remain relatively stable within a small interval [N1, N2]
- #0: TPNs or Prrs are all zeros at the end of each fumigation

Median dose (mg l^{-1})	Immigration number (per day)			
	N0	N20	N100	N500
TPN				
0.14 (D14)	#0	#0	#0	~[8,12]
0.11 (D11)	${}^{84}\downarrow$ #0	${}^{81}\downarrow_{\sim[8, 14]}$	${}^{\sim[94, 98]}\downarrow_{\sim[47, 53]}$	${}_{114}\uparrow^{\sim[270, 293]}$
0.08 (D08)	${}_{960}\uparrow^{4500}$	~[752, 1017] $\uparrow^{1800}$	${}_{942}\uparrow^{2749}$	${}_{1181}\uparrow^{8825}$
Prr				
0.14 (D14)	#0	#0	#0	~[0.08, 0.4]
0.11 (D11)	${}_{0.66}\uparrow^{1.0}\downarrow$ #0	${}^{\sim[0.65, 0.69]}\downarrow_{0.38}$	${}^{\sim[0.57, 0.59]}\downarrow_{0.45}$	~[0.49,0.61]
0.14 (D08)	${}_{0.23}\uparrow^{0.99}$	${}_{0.23}\uparrow^{0.79}$	${}_{0.22}\uparrow^{0.54}$	${}_{0.22}\uparrow^{0.44}$

4. CONCLUSION

It can be seen clearly from the above pattern analyses that phosphine dose consistency is the key factor in avoiding evolution of resistance to phosphine and population increase in *R. dominica*. When a high and consistent dose is achieved, there is no problem with population numbers or evolution of resistance, regardless of immigration rate. When the dose achieved is very inconsistent, there is always a problem with population numbers or evolution of resistance, more so as immigration rate increases.

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