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COMPUTER MODELING FOR SIMULATING STORED PRODUCT INSECT PEST POPULATION DYNAMICS AND INSECTICIDE RESISTANCE POTENTIAL IN FOOD PROCESSING PLANTS

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ABSTRACT

Routine stored product pest management strategies are practiced without valid pre and post treatment insect density estimations. Therefore, the degree and duration of insect suppression obtained are often unknown. A preliminary computer model simulating *T. castaneum* population growth was developed using existing biological data to understand population dynamics in food processing facilities. This model will be useful in developing efficient stored-product pest management programs and testing alternative control methods. With a very limited number of stored-product protection agents available today, the need to evaluate the potential for insecticide resistance development to a fumigant is important. Therefore, the potential for insecticide resistance development to sulfuryl fluoride (SF), a gas fumigant, being developed by Dow AgroSciences, LLC, for post harvest fumigation, was simulated using a Sequential Quantitative Insecticide Resistance Model. This model integrates probable stored-product insect exposure scenarios for SF gas fumigant with several key factors that influence resistance development, such as biology, genetics and operational considerations in predicting probability of insecticide resistance. This validated model indicated a very low probability for any potential resistance development in *T. castaneum*, a key pest that has a history of becoming resistant to existing fumigants.

INTRODUCTION

It is often difficult to predict when a stored-product insect pest will reach or has reached damaging levels and which control method, or combinations of methods, will provide the best control. Depending upon the facility and commodity, various sampling methods could be employed to detect insect infestation. However, relating the number of insects in a sample to actual population size in the facility is difficult. Because of this, routine chemical applications especially with fumigants are commonly done without valid pre- and post-treatment insect density estimations. Therefore, the degree and duration of insect suppression obtained are often unknown. The result is unnecessary treatments or commodity damage due to delayed treatments.

Computer simulation models have been important tools for scientific investigation in nearly all areas of science. In particular, simulation models have been extensively used to evaluate ecology, resource management and integrated pest management. A computer simulated population model that will indicate the pest population development in stored commodities could be useful for predicting optimum control strategies.

This paper will discuss two computer models under development by Dow AgroSciences. The first model targets population dynamics of the red flour beetle, *Tribolium castaneum*, an important stored-product insect pest. Simulations of *T. castaneum* population growth integrate an insect growth model based on life history, and other environmental factors. This model will be useful in developing efficient stored-product pest management programs and evaluating alternative pest control methods.

Dow AgroSciences is developing sulfuryl fluoride (SF) for post harvest fumigation. With a very limited number of stored-product protection agents available today, the need to evaluate the potential for insecticide resistance development to a fumigant is important. Therefore, the second model targets the insecticide resistance development potential for SF using the Sequential Quantitative Insecticide Resistance Model (SQUIRM). This model integrates probable stored-product insect exposure scenarios for SF gas fumigant with several key factors that influence resistance development, such as biology, genetics and operational considerations in predicting probability of insecticide resistance.

MATERIALS AND METHODS

Tribolium castaneum population model

T. castaneum population growth was modeled using existing information on rate of insect development, plus models of insect development stages using time delays and a large array of biological data on adult stages at different times. The array was used in a temperature-dependent model of egg-production. Immigration was assumed at a rate to fit available field data. The population model consisted of a sequence of life stages. Each life stage was divided into k age classes holding a specified number of individuals. Development was modeled according to the distributed delay procedure, in which individuals flow through the age classes at a certain rate (Manetsch, 1976). As individuals leave the last age class of one stage, they enter the 1st age class of the next stage. The k parameter determines the variance s^2 around the mean developmental time L, $s^2 = L^2/k$ (Manetsch, 1976). In a food processing plant, variance has two sources namely genetics and environmental heterogeneity. The variance on developmental time was determined using published information. Data used were from White (1987) and Driscoll *et al.* (2000). Mean values of development period and age-specific fecundity and mortality were used to calculate the intrinsic rate of increase r_m (Birch, 1948). Details on the data ranges are given in Beckett *et al.* (1994).

Sequential Insecticide Resistance Model (SQUIRM)

SQUIRM uses models from scientific literature with local enhancements to assess insecticide resistance potential for discovery molecules at Dow AgroSciences LLC, Indianapolis, IN. This model is designed based on a population dynamics approach by tracking the size and genetic mix of a population for many generations. The inputs include biological, genetic and operational factors. The effects of climate and spatial variability are not included in the model.

Biological factors: Almost every facet of a pest's biology influences the rate at which it can adapt to pesticides. The SQUIRM model currently assumes four distinct life stages, nominally labeled egg, larva, pupa and adult. For each stage the model incorporates: the number of days spent in each life stage, survivorship during this life stage and percent of the population in each life stage that is in refugia and thus completely avoiding a pesticide application and the corresponding selection pressure. Life table information also include: numbers of eggs laid per day or per adult stage (fecundity); day of adult life when egg laying commences; day of adult life when egg laying ceases; male female ratio; number of generations per year; and presence of distinct or overlapping generations. Winter survivorship information such as, presence or absence of an extended dormancy, life stage when the insect over-winters and over-winter survivorship rate are also included in the model. Other biological considerations such as number of individuals per unit area that enter the sampling area per generation (immigration rate), density-dependent effects such as rate limiting life stages and carrying capacity also play an important role in predicting resistance development in this model.

Genetic factors: Several genetic factors such as gene dominance, resistance mechanism and degree of cross-resistance to other insecticides play an important role in the rate of development of insecticide resistance in insects. In the current model, trait-conferring resistance is assumed to be governed by a single autosomal gene with two alleles. Possible genotypes are homozygous resistant (RR), heterozygous (RS), and homozygous susceptible (SS). The initial frequency of the allele is set at 0.0001 and a population is characterized as resistant when the frequency has increased over the set limit. A 1:1 sex ratio and random mating are assumed. An important factor that is incorporated into this model is the fitness penalty for RR and RS genotypes when compared to the SS genotypes. This penalty is handled in the model by the input of lower egg production or increased mortality for the RR and RS genotypes.

Operational Factors: Operational considerations incorporated in this model include the fumigant use rate, application frequency and rotational pattern. The model predicts resistance development based on the LD_{50} and LD_{95} by life stages and for each genotype (RR, RS and SS). Resistance predictions are also dependent upon the defined product failure (e.g., when the product provides <50% control when used at the original application rate), and initial population size.

RESULTS AND DISCUSSIONS

Tribolium castaneum population dynamics

Several workers have used simulation modeling as a low cost method of studying the dynamics of stored-product pests. In the case of food processing plants, the structural complexity of the system makes it difficult to estimate actual numbers of insects present in the structure. Therefore, simulation modeling becomes a particularly important tool for examining the effects of control strategies. Environmental factors such as temperature and humidity (Fig. 1) influenced the form of the model chosen to fit the data. Sharp insect mortality temperature cut-offs, above which an insect population cannot survive, were observed. The simulation data clearly indicated the effect of temperature and humidity on simulated population growth. For example, at 22.5°C, the population growth follows a positive trend at 50% r.h., whereas it follows a negative trend at 40% r.h.

T. castaneum population growth adjusted for varying temperatures assumed inside a food processing facility is presented in Fig. 2. In this simulation, initial population was set at 100 individuals (mixed population assumed to follow a ratio of 1:4:2:3 egg, larva, pupa and adult, respectively) on day 1. Since the economic threshold will vary by food processing facility, a hypothetical action threshold of 1,000 individuals was established. When the simulations were conducted at 60% r.h., the population reached the action threshold level in 187 days. However, at 50% r.h., the population did not reach the action threshold until 217 days, about 30 days later. The population growth was considerably slower when the simulation was run at 40% r.h.. It took 294 days for the population to reach the hypothetical action threshold.

A model in this stage of development should only be used as an indicator of the relative importance of environmental factors and pest control practices on insect pest infestation levels over time. Dow AgroSciences is currently working to validate this type of population growth model, and then to use an enhanced version as a predictor of the performance of various stored product insect management practices. As it is, the model is not predictive, because it has not been validated with field data. Even when validated, this model will provide only limited direction to pest management professionals unless customer-defined action levels and economic thresholds have been established.

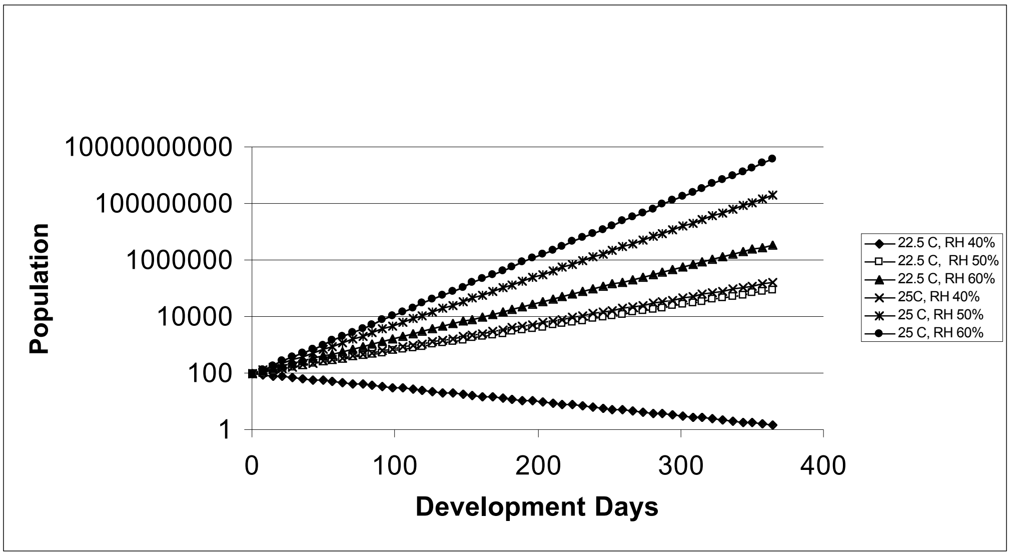

Fig. 1. Simulated *Tribolium castaneum* population growth under different environmental conditions.

SQUIRM model

During 1972-73, the Food and Agricultural Organization of the United Nations (Champ and Dyte, 1976) undertook a global survey of the susceptibility of stored-product insects to pesticides. This report revealed that almost 10% of the insect populations sampled in different countries included phosphine (PH_3) resistant insects. A later survey in Bangladesh, where PH_3 fumigations were reported to be failing, showed very high levels of resistance to PH_3 in many species of stored-product insects (Tyler *et al.,* 1983).

Early reports of PH_3 resistance in *T. castaneum* were based on selection of resistant insect strains in the laboratory. Winks (1969) reported a 6.5-fold increase in resistance of a twice-selected strain of *T. castaneum.* Kem (1977), and Saxena and Bhatia (1980) reported 12 and 5.9 fold increases in resistance of adult *T. castaneum* after 10 and 16 generations of selection respectively. Winks (1986) speculated that either genes for PH_3 resistance were already present at lower frequencies or PH_3 treatment caused high rates of mutation. Winks (1986) also reported that there was no appreciable change in the level of PH_3 resistance in a laboratory-selected strain of *T. castaneum* maintained for 17 years without any further selection. In their worldwide FAO survey, Champ and Dyte (1976) indicated that the highest level of

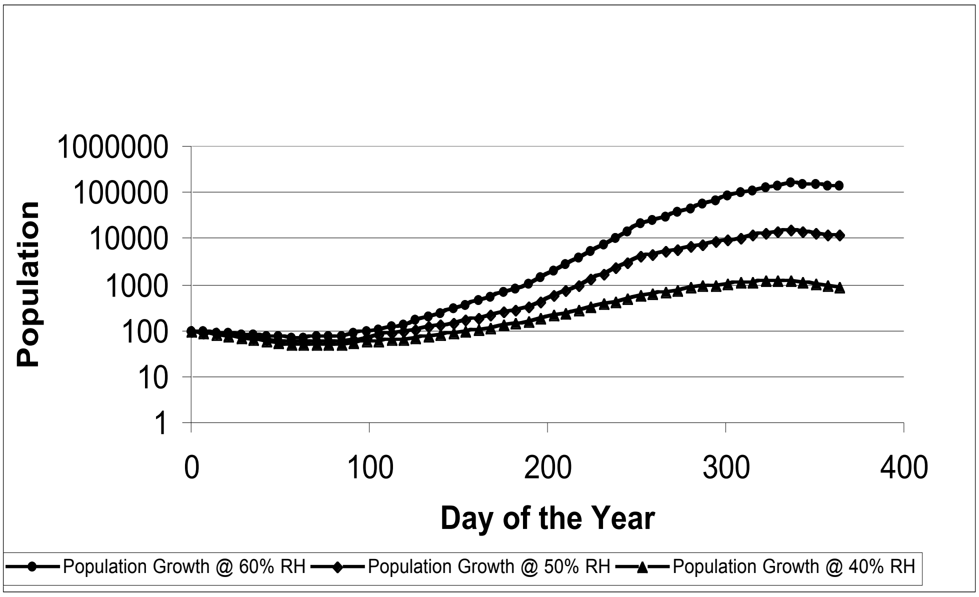

Fig. 2. Effect of relative humidity on *Tribolium castaneum* population growth simulations.

resistance across the sampled *Tribolium* species was 10-fold. Laboratory selection of some of the field strains further increased the levels of resistance to PH_3.

The SQUIRM model used in this study was intended to predict the probability of insecticide resistance development in *T. castaneum* to different exposure scenarios of sulfuryl fluoride. The resistance simulation model was first validated using data collected from the literature on PH_3 and *T. castaneum.* Due to lack of information on SF regarding resistance gene frequencies, and fitness penalties, assumptions were made and the model was run at different levels of these factors. Based on the available data, and assumed practical levels of gene frequencies, it was concluded that the probability of SF resistance in *T. castaneum* is negligible. The major factors that retard development of resistance in *T. castaneum* when SF is used as a food processing plant fumigant, are: high immigration rates of insects which dilute the resistant insect pool, low selection pressure (low frequency of application and no residue), presence of overlapping generations and assumed lack of cross resistance to sulfuryl fluoride. Hence, under normal food processing facility fumigation procedures, the likelihood of product failure due to resistance is negligible.

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