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ORIGINAL PAPER

Using a population growth model to simulate response of *Plodia interpunctella* Hübner populations to timing and frequency of insecticide treatments

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Abstract Management strategies for urban and stored-product pests are chosen for a variety of attributes including cost, efficacy, and human safety. Insect growth regulators, which are low-risk alternatives to traditional neurotoxic insecticides, may be valuable management options. However, as these new products become available there is a need to determine efficacy in regard to survival after exposure and effect on population dynamics, so that overall value of these treatment methods can be determined. This study was conducted to predict the effects of methoprene and two conventional insecticides combined with methoprene on development of *Plodia interpunctella* Hübner populations on an optimal diet and on a suboptimal diet. Effects on populations were simulated using a modified temperature-based growth model at 24, 30, and 35 °C, and the effects of timing and frequency of insecticide treatments were determined. The results of this simulation study predict rapid population growth of *P. interpunctella* populations on optimal and suboptimal diets, and that single applications of a contact insecticide or aerosol may not be sufficient to manage *P. interpunctella* populations over a 6-month period.

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Introduction

Plodia interpunctella Hübner (Indianmeal moth) is a cosmopolitan pest of stored products. Insecticides are routinely used for management of *P. interpunctella*, but it can be difficult to determine the long-term effects of insecticides on populations of this pest. This is particularly true in warehouses, where *P. interpunctella* is often the major pest, because of the complexity of the warehouse environment where temperatures vary with season and different combinations of products are stored throughout the year. *P. interpunctella* feeds on numerous types of stored products that might be found together in the same warehouse, and its rates of development and survivorship on these different products may vary (Mohandass et al. 2007). These conditions make it difficult to generalize from field studies on efficacy of insecticides in warehouses. Computer simulation models can be useful tools for investigating long-term effects of insecticides and other management tools on *P. interpunctella* populations in warehouses.

The insect growth regulator methoprene and methoprene in combination with two conventional insecticides, esfenvalerate and synergized pyrethrins, may be used in warehouses for control of *P. interpunctella*. In this study, we predict *P. interpunctella* population changes in response to methoprene and combination treatments with esfenvalerate and synergized pyrethrins at different temperatures and varying application intervals by using a computer simulation model originally developed and validated for *P. interpunctella* populations developing on whole corn, but

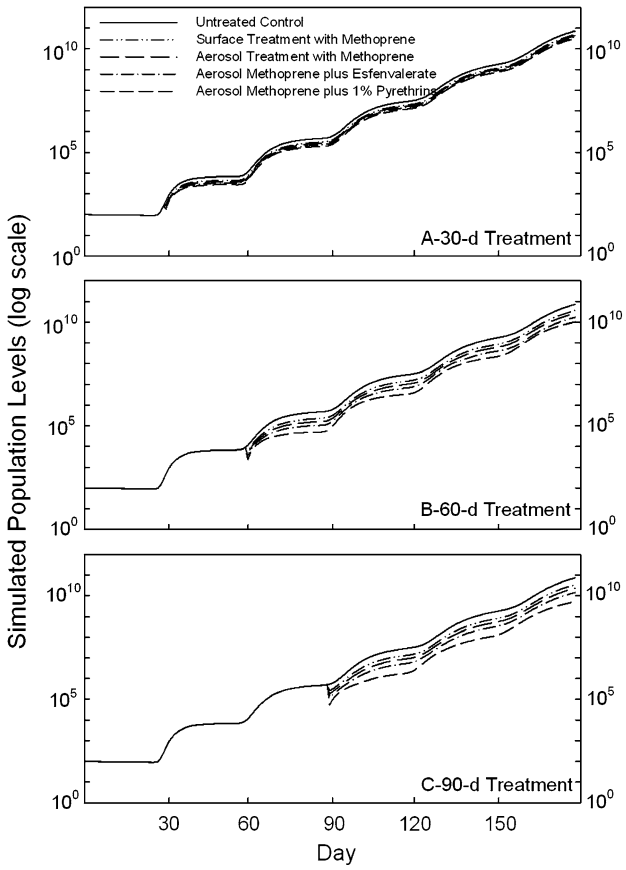

Fig. 1 Effect of a one-time application of different insecticide treatments on *Plodia interpunctella* population development (including all stages from egg to adult and shown as population level +1 to allow use of log scale) on an optimal diet. One hundred eggs were present beginning on day 1 of simulations, and simulations were run for 180 days at a constant temperature of 24 °C. Insecticide treatment was applied at day 30 (**a**), 60 (**b**), or 90 (**c**)

modified for *P. interpunctella* developing on an optimal diet, wheat diet, and a suboptimal diet, raisins.

Materials and methods

Model background

Once a model is developed to predict population growth rates on one type of diet, it can be modified to show rates of population growth after insecticide application or on other types of diets (Throne 1995). The base computer model used in this study was developed by Throne and Arbogast (2010) for simulating populations of *P. interpunctella* feeding on corn. We modified the model (complete description of modifications to model in Fontenot et al. 2012) to simulate the effects of diet and insecticides on *P. interpunctella* populations. The diets chosen for the simulations were an enriched wheat diet, which we use to rear our *P. interpunctella* colony because it is an optimal diet for development, and raisins, which are a suboptimal diet. The enriched wheat diet is composed of cracked wheat and shorts (4.4 kg), brewer's yeast (22 g), sorbic and benzoic acid (9.5 g each), honey (240 ml), glycerin (240 ml), and water (120 ml). Validating the modified models in the field is impractical because of the complexity of the warehouse environment, as mentioned above, but use of such unvalidated models has proven useful for identifying general trends in response to management strategies (e.g., Sinclair and Alder 1985; Longstaff 1988; Throne 1989).

Survivorship data for exposure to insecticide treatments

The model was developed using data for egg to adult development, so mortality after insecticide treatment is applied to all immature insects in the population. Mortality was simulated to occur at noon on the day of insecticide treatment. We did not apply mortality to adults because there are no data to indicate that methoprene kills adult Lepidoptera, and there are no data which can be used to estimate effect of the other insecticides tested on adults. Mortality for each insecticide was calculated using the label rate for surface or aerosol application.

Four insecticide treatments were selected for simulations based on results from Jenson et al. (2009, 2010a, b), where insecticide-susceptible laboratory colonies were tested. These were methoprene as a surface treatment, methoprene as an aerosol treatment, methoprene, and esfenvalerate applied together as an aerosol, and methoprene and 1 % synergized pyrethrins applied together as an aerosol. In Jenson et al. (2009), survivorship was 45.07 % after application of methoprene alone as a surface treatment, and this value included survival across all surface types tested when *P. interpunctella* eggs were exposed to the label rate. Rate of survivorship for methoprene at the label rate delivered as an aerosol was 30.99 %, and this value was an average across all exposure types of data from Jenson et al. (2010b). Survival for the aerosol treatment combination of the label rates of methoprene and esfenvalerate was 17.7 %, as determined from egg exposure data in Jenson et al. (2010a). The combination aerosol treatment of methoprene and 1 % synergized pyrethrins, both at the label rate for aerosol application, was 5.37 % based on data in Jenson et al. (2010b).

Inputs to the model

Simulations were run at three temperatures (24, 30, and 35 °C) to address seasonal variation in temperature, with a beginning population of 100 eggs and no adult moths. This population level represents one female entering a warehouse and laying 100 eggs in just a few days before dying, a rate of oviposition that is reasonable for *P. interpunctella*

Table 1 Simulated population levels (including all stages from egg to adult) of *Plodia interpunctella* on suboptimal and optimal diets after 180 days at 24, 30, and 35 °C with single-insecticide treatments at days 30, 60, and 90

	Treatment at day 30			Treatment at day 60			Treatment at day 90		
	24 °C	30 °C	35 °C	24 °C	30 °C	35 °C	24 °C	30 °C	35 °C
Suboptimal diet									
Untreated Control	4639	2129	4	4639	2129	4	4639	2129	4
Surface Methoprene	2088	958	2	2088	1297	2	2658	958	2
Aerosol Methoprene	1431	660	1	1431	1072	1	2117	640	1
M + E	816	374	1	816	884	1	1670	374	1
M + 1 % P	247	106	0	247	694	0	1217	106	0
Optimal diet									
Untreated Control	7.27E + 10			7.27E + 10			7.27E + 10		
Surface Methoprene	4.87E + 10			3.65E + 10			3.37E + 10		
Aerosol Methoprene	4.25E + 10			2.67E + 10			2.30E + 10		
M + E	3.67E + 10			1.71E + 10			1.42E + 10		
M + 1 % P	3.14E + 10			1.02E + 10			5.33E + 09		

The label M + E indicates the methoprene + esfenvalerate treatment discussed in the text. Similarly, the M + 1 % *P* indicates the methoprene + 1 % pyrethrins treatment

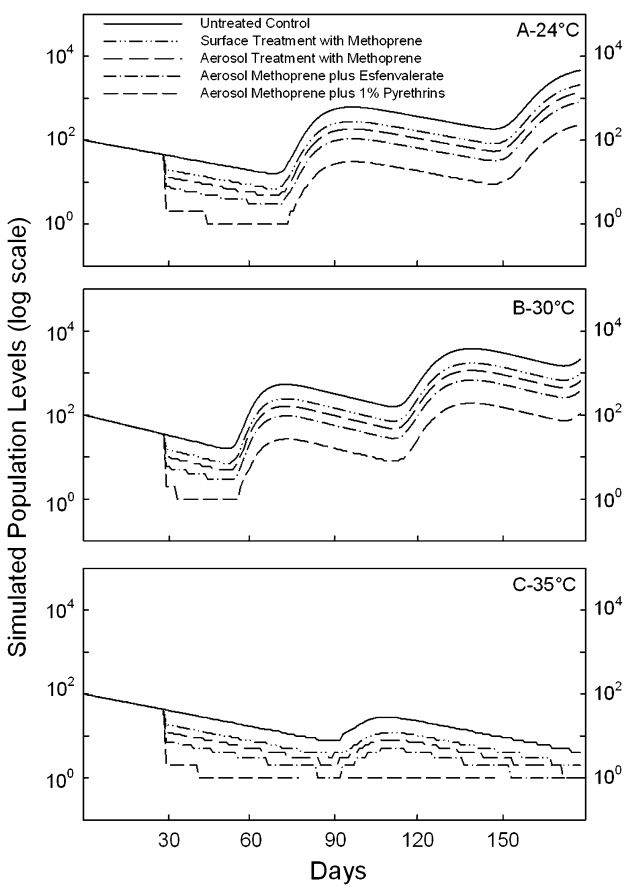

Fig. 2 Effect of a one-time application at day 30 of different insecticide treatments on *Plodia interpunctella* population development (including all stages from egg to adult and shown as population level +1 to allow use of log scale) on a suboptimal diet. One hundred eggs were present beginning on day 1 of simulations, and simulations were run for 180 days at 24 °C (**a**), 30 °C (**b**), and 35 °C (**c**)

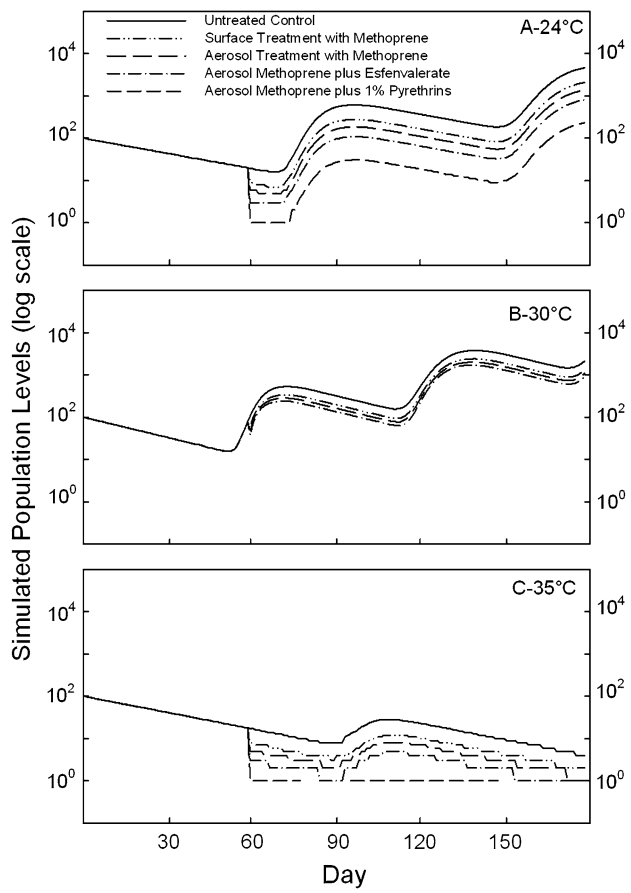

Fig. 3 Effect of a one-time application at day 60 of different insecticide treatments on *Plodia interpunctella* population development (including all stages from egg to adult and shown as population level +1 to allow use of log scale) on a suboptimal diet. One hundred eggs were present beginning on day 1 of simulations, and simulations were run for 180 days at 24 °C (**a**), 30 °C (**b**), and 35 °C (**c**)

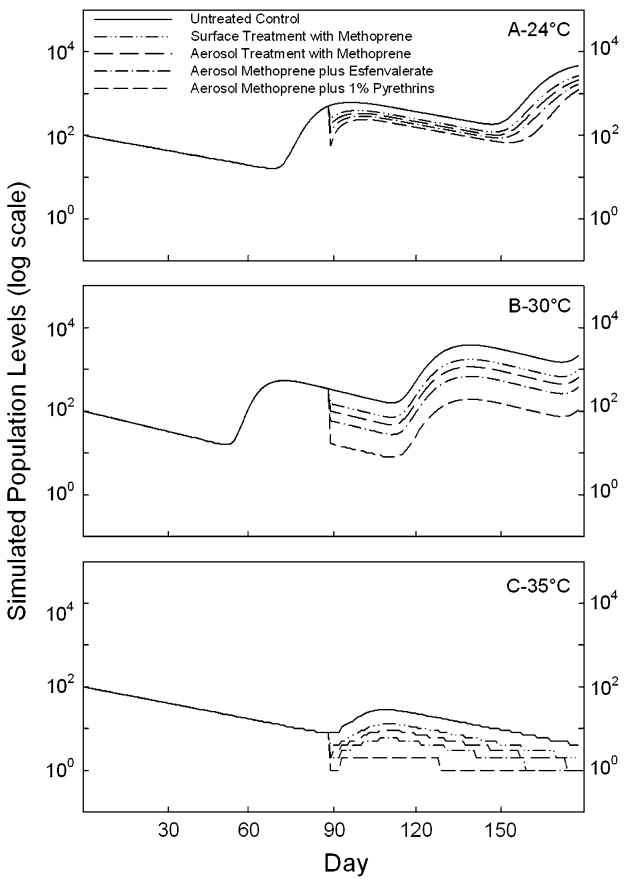

Fig. 4 Effect of a one-time application at day 90 of different insecticide treatments on *Plodia interpunctella* population development (including all stages from egg to adult and shown as population level +1 to allow use of log scale) on a suboptimal diet. One hundred eggs were present beginning on day 1 of simulations, and simulations were run for 180 days at 24 °C (**a**), 30 °C (**b**), and 35 °C (**c**)

(Arbogast 2007). The three temperatures were chosen to be within the range of optimal *P. interpunctella* development, and these temperatures are within the range of temperatures that might occur in a warehouse. We investigated the impact of timing and frequency of insecticide applications on growth of *P. interpunctella* populations, which for our simulations is reported as insects in all stages of development (egg through adult). We examined the impact of timing of insecticide applications by simulating effects of one-time applications of each insecticide occurring at 30, 60, or 90 days from the first day of the simulations at the three temperatures, and we examined the impact of frequency of insecticide applications by simulating effects of monthly or biweekly recurring insecticide treatments at the three temperatures.

Statistical comparison of treatments is not possible because each simulation results in one outcome (a population level after a certain number of days). However, the intent of the simulations is to examine general trends resulting from different management strategies, as has been done in previous studies (e.g., Sinclair and Alder 1985; Longstaff 1988; Throne 1989).

Results

When each insecticide was applied only once at 30, 60, or 90 days at 24 °C, there was extensive development of *P. interpunctella* populations on wheat diet even with the methoprene + 1 % pyrethrins which had a rate of survivorship of only 5 % (Fig. 1; Table 1). Thus, we do not show data for higher temperatures on wheat diet. Population levels

Table 2 Simulated population levels (including all stages from egg to adult) of *Plodia interpunctella* on optimal and suboptimal diets after 180 days at at 24, 30, and 35 °C and with recurring insecticide treatments every 14 and 30 days

Treatments simulated	Optimal diet			Suboptimal diet		
	24 °C	30 °C	35 °C	24 °C	30 °C	35 °C
Monthly treatments						
No Treatment	7.27E + 10	1.67E + 14	4.49E + 06	4640	2130	4
Surface Methoprene	1.16E + 09	3.24E + 12	1.45E + 05	53	33	0
Aerosol Methoprene	1.68E + 08	6.22E + 11	3.72E + 04	6	5	0
Methoprene + Esfenvalerate	1.71E + 07	6.91E + 10	6.95E + 03	0	0	0
Methoprene + 1 % Pyrethrins	7.51E + 05	3.90E + 09	8.22E + 02	0	0	0
Biweekly treatments						
No treatment	7.27E + 10	1.67E + 14	4.49E + 06	4640	2130	4
Surface methoprene	6.91E + 06	7.26E + 07	2.20E + 03	1	0	0
Aerosol methoprene	1.86E + 05	3.24E + 07	1.18E + 02	0	0	0
Methoprene + Esfenvalerate	9.93E + 02	1.26E + 07	0.00E + 00	0	0	0
Methoprene + 1 % Pyrethrins	0.00E + 00	2.27E + 03	0.00E + 00	0	0	0

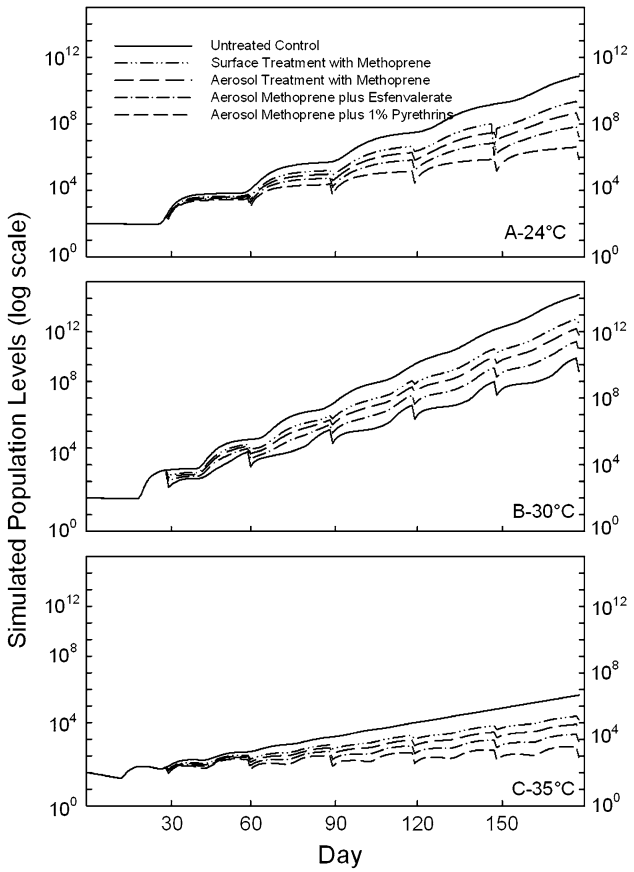

Fig. 5 Effect of multiple insecticide applications on *Plodia interpunctella* population development (including all stages from egg to adult and shown as population level +1 to allow use of log scale) on an optimal diet. One hundred eggs were present beginning on day 1 of simulations, and simulations were run for 180 days at 24 °C (**a**), 30 °C (**b**), and 35 °C (**c**). Insecticide treatment was applied for the first time at day 30 and at 30-day intervals for the remainder of the simulation

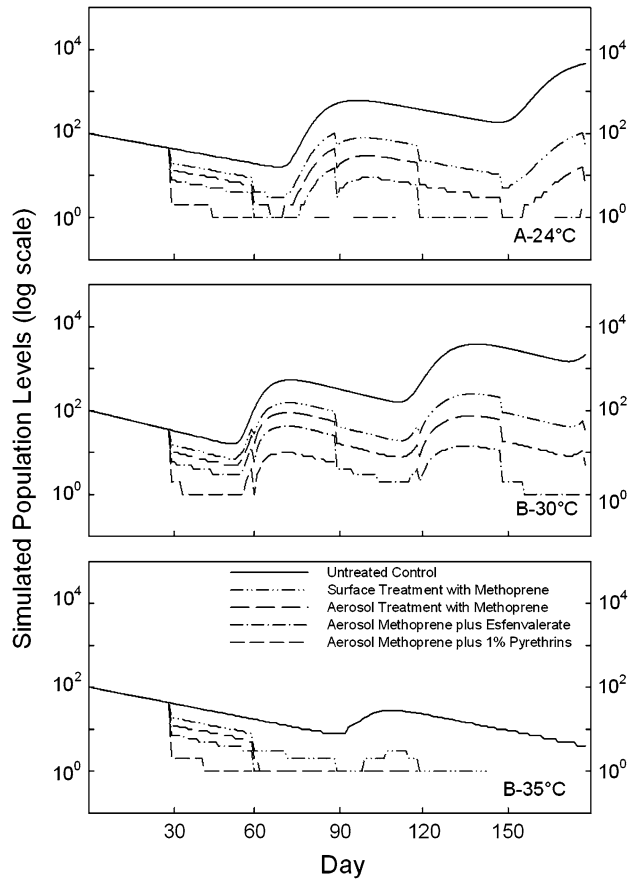

Fig. 6 Effect of multiple insecticide applications on *Plodia interpunctella* population development (including all stages from egg to adult and shown as population level +1 to allow use of log scale) on a suboptimal diet. One hundred eggs were present beginning on day 1 of simulations, and simulations were run for 180 days at 24 °C (**a**), 30 °C (**b**), and 35 °C (**c**). Insecticide treatment was applied for the first time at day 30 and at 30-day intervals for the remainder of the simulation

on wheat diet were always relatively numerically higher the earlier a treatment was applied (i.e., population levels within an insecticide treatment type were greater when insecticide was applied at 30 > 60 > 90 days). The relative order of population growth among insecticide treatments was directly related to survivorship levels for each given treatment (i.e., population levels were numerically greater for surface methoprene treatments with 45.07 % survivorship > aerosol methoprene with 30.99 % survivorship > aerosol methoprene + esfenvalerate with 17.7 % survivorship > aerosol methoprene + 1 % pyrethrins with 5.37 % survivorship).

One-time insecticide applications on raisins resulted in similar patterns of population decrease as on wheat diet, but ending population levels were numerically much lower than on wheat diet (Figs. 2, 3, 4; Table 1). At 35 °C, populations were almost eliminated on raisins whether or not an insecticide was applied (Figs. 2c, 3c, 4c; Table 1).

All monthly and biweekly insecticide treatments reduced population levels at the end of 180 days (Table 2), relative to the untreated control, but the populations on wheat diet showed a continual population increase (Figs. 5, 7). Predicted population levels were numerically lower on raisins than on wheat diet (Figs. 6, 8; Table 2). At all three temperatures, monthly aerosol combination treatments with methoprene and 1 % pyrethrins or esfenvalerate were predicted to eliminate populations on raisins. Biweekly surface and aerosol treatments on wheat diet (Fig. 7) resulted in the same population trends as the monthly treatments (Fig. 5), but the biweekly insecticide treatments always resulted in numerically lower population levels than in the monthly treatments. The simulations predicted that the combination of methoprene + pyrethrins applied biweekly would eliminate populations at 24 and 35 °C. *P. interpunctella* populations on raisins were reduced to

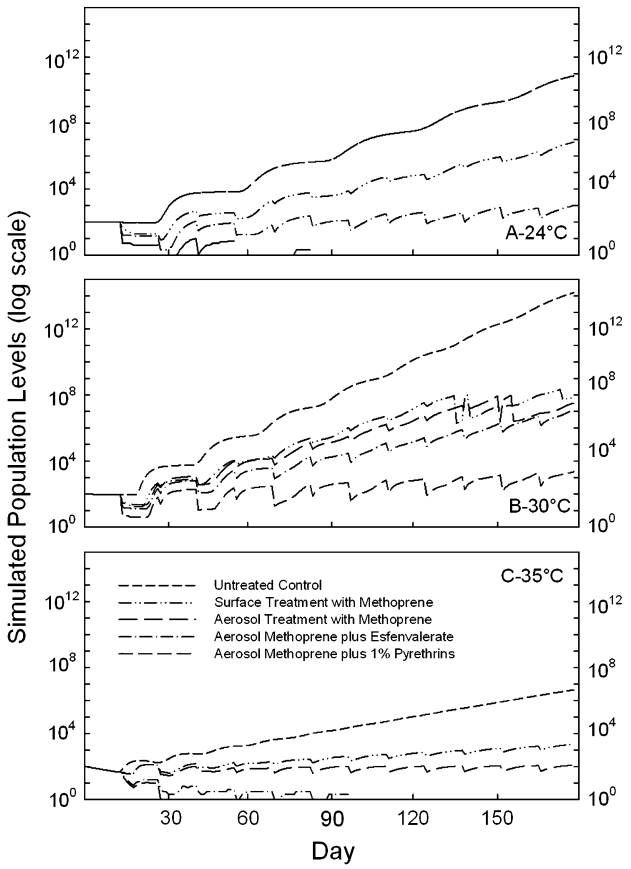

Fig. 7 Effect of multiple insecticide applications on *Plodia interpunctella* population development (including all stages from egg to adult and shown as population level +1 to allow use of log scale) on an optimal diet. One hundred eggs were present beginning on day 1 of simulations, and simulations were run for 180 days at 24 °C (**a**), 30 °C (**b**), and 35 °C (**c**). Insecticide treatment was applied for the first time at day 14 and at biweekly intervals for the remainder of the simulation

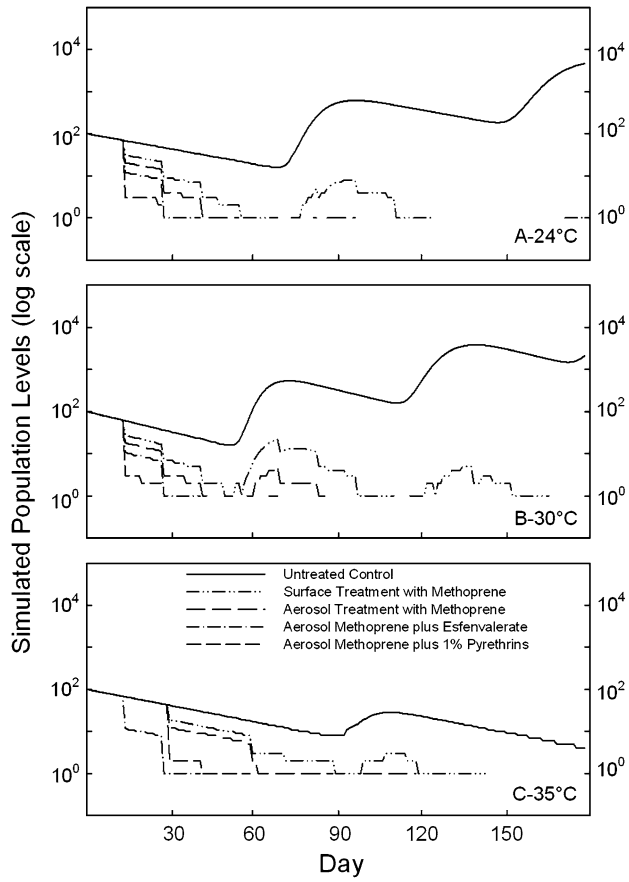

Fig. 8 Effect of multiple insecticide applications on *Plodia interpunctella* population development (including all stages from egg to adult and shown as population level +1 to allow use of log scale) on a suboptimal diet. One hundred eggs were present beginning on day 1 of simulations, and simulations were run for 180 days at 24 °C (**a**), 30 °C (**b**), and 35 °C (**c**). Insecticide treatment was applied for the first time at day 14 and at biweekly intervals for the remainder of the simulation

nearly zero in the first three biweekly treatments for all insecticide treatments (Fig. 8).

Discussion

The results of our simulations show little population decrease of *P. interpunctella* on an optimal diet as a result of insecticide treatments, except when the combination treatment of methoprene with pyrethrins aerosol was applied every 14 days. This combination has shown efficacy in small-scale shed studies (Jenson et al. 2010a, b). In our simulations, the responses to the various insecticides were simulated by assuming that food was not a limiting factor, which led to high population levels on the optimal diet. Survival after insecticide treatment was conservatively calculated to include only mortality to immatures, and the simulations assume adults were not affected by the insecticide treatment. Pyrethrin might be expected to cause some adult mortality, but, since it dissipates rapidly, would have little residual efficacy (Arthur 2010). Therefore, using methoprene in combination with conventional insecticides might be effective in a food warehouse, where the different food sources might not be as optimal for population growth as the wheat diet.

Population growth of *P. interpunctella* on the optimal and suboptimal diets was very different as a result of the mean developmental times and survivorship values for each diet. The optimal diet is an example of a "worst-case scenario" for pest management as it supports rapid population growth. Populations on the optimal diet were predicted to grow so rapidly that population levels rebounded to pre-treatment levels within a few days even with an insecticide treatment that caused 94 % mortality. Therefore, timely management of *P. interpunctella* in any area

containing products that support optimal growth of *P. interpunctella* populations would be crucial to avoid product loss.

With their high-reproductive capacity, simulated *P. interpunctella* populations increased on raisins, even though *P. interpunctella* typically has low survival and long developmental times on this commodity (Johnson et al. 1995). Despite this population increase, biweekly or monthly applications of methoprene + 1 % pyrethrins or esfenvalerate eliminated *P. interpunctella* populations on raisins, as did biweekly methoprene aerosol treatments. The dried fruit and nut industries use fumigants for control of *P. interpunctella* (Johnson and Vail 1989; Hilton and Banks 1997; Johnson et al. 2002), and our simulations show that it may be possible to also use aerosol applications in sites where products are processed, bagged, and stored.

There are unique challenges to working in a finished stored product or warehouse situation. In a food warehouse or manufacturing facility, temperatures typically do not fluctuate day-to-day, and instead follow broad seasonal patterns. Temperatures during the cooler months may not be sufficient to eliminate populations (Kaliyan et al. 2007a, b; Johnson 2007), especially in climate-controlled facilities that allow population levels to remain high throughout the year. There are also constraints on insecticides that may be applied and on the timing of those applications (Arthur 2008), and there are other control strategies that can be effective for management of *P. interpunctella*. Heat (Roesli et al. 2003; Mahroof and Subramanyam 2006), biological agents such as granulosis virus (Vail et al. 1991; Bjornstad et al. 1998), and low-temperature aeration treatments (Mason et al. 1997; Kaliyan et al. 2007b) have all been modeled using similar biological parameters as we used in our simulations. Other management options include good sanitation practices (Fields and White 2002) and insect-resistant packaging (Mullen 1994). Our results indicate that one-time applications of the insecticide treatments tested would not be expected to provide adequate control of *P. interpunctella* for a 6-month period in a warehouse, while some of the biweekly and monthly insecticide treatments were predicted to be effective for management of *P. interpuctella*.

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