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Review

Biology and management of *Plodia interpunctella* (Lepidoptera: Pyralidae) in stored products[☆]

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Abstract

Plodia interpunctella (Hübner), the Indian meal moth, is a world-wide insect pest of stored-products and processed food commodities. It can infest a variety of products and is perhaps the most economically important insect pest of processed food. In this review, we summarize the biology of *P. interpunctella*, discuss oviposition and development in relation to temperature, environment and food source, examine studies involving sampling and detection, describe various aspects of integrated control, summarize the current knowledge regarding management of *P. interpunctella*, and address potential areas for new research. The use of reduced-risk insecticides, non-chemical control, targeted pest management through spatial analysis and other means of identifying specific locations of infestations, and computer models that simulate population growth, are examples of some of those new areas of research. Published by Elsevier Ltd.

Keywords: *Plodia interpunctella*; Biology; Control; Research

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1. Introduction

The Indian meal moth, *Plodia interpunctella* (Hübner), is a major economic insect pest of stored products and is found on every continent except Antarctica (Rees, 2004). There are no records suggesting that *P. interpunctella* could migrate or disperse over continental distances. However, *P. interpunctella* has been found within infested commodities in commercial ocean freight shipments (Schulten and

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Roorda, 1984) and in food products imported into the United Kingdom from Africa (Cox, 1979).

One of the first comprehensive scientific studies of *P. interpunctella* was undertaken by Hamlin et al. (1931), who categorized the insect as a pest of grain, grain-based crops, and more than 20 different nuts, fruits, and candies from the agricultural system in the state of California in the United States of America (USA). They also described the economic consequences of infestations through returned infested products. The products or groups of products that have been reported to be infested by *P. interpunctella* are listed in several publications (Johnson et al., 1992, 1995; Sedlacek et al., 1996; Nansen and Phillips, 2003, 2004; Nansen et al., 2004a). *Plodia interpunctella* is an external feeder. The larvae continuously spin a silken web both inside and on top of the food surface, and feed within the web. The webbing contains larval excreta (frass) and exuvia (cast skins), and gives an unpleasant odor to the infested commodity. The infested commodity is sometimes covered on the surface with a thick mat of silken webbing. Infestations of *P. interpunctella* can cause direct product loss and indirect economic costs through pest control costs, quality losses, and consumer complaints (Phillips et al., 2000a).

In the USA, the continuing loss of chemical insecticides through regulatory action, new laws and interpretations of those laws, economic costs of pesticide regulations, and consumer preferences and expectations, have important consequences for the management of *P. interpunctella* and other stored-product insects (Arthur, 1996). The impending loss of the fumigant methyl bromide through compliance with the Montreal Protocol (Anonymous, 2004) will undoubtedly further affect management programs for *P. interpunctella*, accelerating the demand for new control strategies (Phillips et al., 2000a, b). The objectives of this review are to: (1) summarize and synthesize the information regarding biology and control in a review format; and (2) to discuss potential areas of new research on management and control of *P. interpunctella*.

2. Biology

Plodia interpunctella is a pyralid moth in the sub-family Phycitinae. Most researchers and workers with stored-product insects are familiar enough with the species that detailed depictions of the life stages are not needed in this review. A general description of all life stages was first given by Hamlin et al. (1931), and there are several more recent summaries and descriptions (Rees, 2004). Detailed morphological descriptions of larvae, pupae and adults were given in Richards and Thomson (1932) and in Hinton (1943), and Heinrich (1956) describes adult wing venation and genitalia of the sexes. There are five larval instars (Allotey and Goswami, 1990). Arbogast et al. (1980) describes the eggs of *P. interpunctella* as being small, with rounded excrescences and prominent carinae, and give a

key for separating the eggs from those of other common stored-product insects.

Oviposition behavior in *P. interpunctella* is influenced by food odor (Phillips and Strand, 1994), and eggs are laid on or near the food surface, often spatially aggregated in some fashion (Mullen and Arbogast, 1977; Arbogast and Mullen, 1978). Deseo (1976) showed fecundity of *P. interpunctella* is increased by food odor and that the eggs are laid in batches near the source of the odor. Orientation of adult *P. interpunctella* towards oviposition sites could be based on primary host-derived or secondary conspecific-insect-derived chemical cues. Phillips and Strand (1994) found that adult *P. interpunctella* oriented towards food odors and laid more eggs on substrates containing food than on those without food, and more eggs were laid on dishes that contained conspecific larval secretions. The adults may lay their eggs near the food surface when the food is inaccessible due to packaging or other barriers, or when the food odors are weak (Silhacek et al., 2003). The presence of oils can also lead to an increase in oviposition of *P. interpunctella* (Nansen and Phillips, 2003). Fecundity of *P. interpunctella* differs greatly from one study to another and is dependent upon several factors, such as type of food, size of the female, provision of drinking water, and physiological state of the female moths (Mbata, 1985). As with other biological parameters for *P. interpunctella*, there is considerable variation among laboratory studies regarding fecundity. Mbata (1985) reported that maximum fecundity occurred at 30 °C, Bell (1975) documents successful breeding but not maximum fecundity at 30 °C, and Johnson et al. (1992, 1995) show egg laying up to 31 °C, dependent in part on the rearing diet. Environmental diurnal cycles and circadian rhythms apparently have little influence on oviposition in *P. interpunctella*, in contrast to other pyralid moth species (Bell, 1981).

The food source is obviously an important factor for determining fecundity and other biological parameters. Allotey and Goswami (1990) recorded mean fecundities of 96.8 on wheat and 174.2 on broken maize, which are much lower than the mean fecundities of 258, 275, and 280 when the young larvae were reared on walnuts, almonds, and wheat bran, respectively (Johnson et al., 1992). In laboratory experiments, the percentage egg hatch also varies according to the type of commodity used for rearing younger stages. On pistachios and almonds, the egg hatch was 88% and 96%, respectively (Johnson et al., 1992), while up to 98.6% of the eggs hatched from adults whose younger stages were reared on different commodities (Allotey and Goswami, 1990). The newly hatched larvae quickly disperse to find food (Sedlacek et al., 1996), and first instars can invade cans containing food through pinholes of diameter 0.39–0.45 mm (Tsuji, 1998, 2000). The invasion decreased as the distance from the food source increased but a large proportion of the larvae were found inside the food, even when the food source was placed up to 38 cm from the release point.

In addition to temperature (Bell, 1975), the type of commodity or food material greatly influences the time required for *P. interpunctella* to complete the life cycle (Williams, 1964; Mbata and Osuji, 1983; Subramanyam and Hagstrum, 1993; Johnson et al., 1995). At 20 and 25 °C; 70% relative humidity (r.h.), the peak emergence of adults from eggs of a laboratory strain reared on wheat feed, yeast, and bran diet was 60 and 34 days, respectively (Bell, 1975). Johnson et al. (1992) recorded development times of 22.6 days at 28.3 °C on bran compared with 31.3, 31.4, and 38.2 days on almonds, pistachios, and walnuts, respectively, with similar patterns at higher and lower temperatures. Egg to adult emergence required 25.7 and 46.1 days when reared at 30 °C and 76% r.h. on broken sorghum and on wheat, respectively (Allotey and Goswami, 1990). Due to such differences in development times, different degree-day estimations may be required for egg to adult development of *P. interpunctella* reared on different commodities (Johnson et al., 1995). Different lower limits of development have also been reported by researchers (Howe, 1965; Bell, 1975; Fields, 1992; Johnson et al., 1995), ranging from 16 to 20 °C, which could also relate to variation in diet, rearing conditions, and geographic differences in particular moth strains. This variation in developmental time also contributes to the difficulty in defining individual stage-specific development time for the five larval stages. In addition, it is difficult to observe larval molts in various diets, and it is possible that frequent disturbance of the larvae to measure head capsules to find other evidence of molting may prolong development time and increase mortality.

Diapause occurs in the 5th or last instar, after feeding has ceased, but environmental cues may occur earlier in the development. Low temperatures can induce diapause (Tzanakakis, 1959; Johnson et al., 1995), as can short photoperiods (Tzanakakis, 1959; Bell and Walker, 1973). In a study by Bell (1976a), *P. interpunctella* entered diapause at 20 and 25 °C when the photoperiod was less than or equal to 13 h. Diapause can also be induced by a sudden drop in temperatures. A Nigerian strain of *P. interpunctella* entered diapause when they were reared at 30 °C up to the third instar stage and then placed at 20 °C (Mbata, 1987). In storage facilities where temperatures are uncontrolled, *P. interpunctella* larvae may enter diapause during the colder months. When suitable conditions re-occur, a sudden increase in moth population occurs, usually during the early spring season (Mason, 2003). In some cases, diapause can be absent in geographic locations where temperatures may not be cool enough to induce it (Prevett, 1971).

Longer photoperiods and higher temperatures terminate diapause in the larvae. At 20 °C, rapid termination of diapause occurred at 16:8 (light: dark) (Bell, 1976b). The effects of density on diapause were first described by Tsuji (1959), who recorded a density-induced diapause. Bell (1976a) also recorded an increase in diapause triggered by a high rearing density in specific populations of

P. interpunctella. The effects of density on the induction of diapause may be determined in part by temperature and experimental conditions, and also other factors such as strain geographic origin (Bell et al., 1979), the photoperiod at specific temperatures and the cold-tolerance of individual strains (Bell, 1982).

The time required for *P. interpunctella* to complete a generation is a complex interaction of temperature, diet, and geographic strain. Emergence of *P. interpunctella* adults and several of the subsequent behaviors are related to photoperiod. In a simulated warehouse condition, upon emergence at the end of the photophase, the moths moved rapidly to the nearby walls or undersides of storage pallets (Silhacek et al., 2003). In a study under natural light/dark cycles across four seasons, Madrid and Sinha (1983) found that the initial peak period of adult movement and oviposition occurred during the early evening hours. As the age of the adults increased, this movement and oviposition became more erratic, without any definite peaks. Mating occurred within the first 24 h (Silhacek et al., 2003).

3. Sampling, detection, and distribution

Sampling of adult populations in the field can be done by a variety of methods, but the primary sampling tool is through pheromone-based trapping of males (Phillips et al., 2000a, b; Mullen and Dowdy, 2001). The pheromone commonly referred to as “ZETA” was one of the first commercial pheromones for stored-product insects, and the response of males to this pheromone has been well documented (Nansen and Phillips, 2003, 2004; Nansen et al., 2004a, b). Although pheromone traps are commonly used in monitoring studies, there are a variety of factors that can influence trap catch including but not limited to density, trap type, visual cues, pheromone composition and trap height (cited in Nansen et al., 2004a). In small shed studies, Nansen et al. (2004a) showed male moths were attracted to traps with a physical surface that simulated a landing platform, but in the absence of such a surface, traps placed low and high in the shed caught more males than other traps in the vertical grid. Trap placement therefore appears to be an important consideration when assessing storage structures for *P. interpunctella*. Larval populations can be sampled through food traps or corrugated cardboard pupation traps, or traps that are designed to catch adult beetles.

Plodia interpunctella can be found in stored grain commodities, though it is usually not a primary pest of those crops. In grain bins, more stored-product insects are found in samples taken from the top layer of the grain mass than from the bottom layers (Hagstrum et al., 1998). The variation in *P. interpunctella* numbers over a period of time, between grain bins, and locations within grain bins differ with the type of sampling method used. In a study by Hagstrum (2000), the majority of *P. interpunctella* were caught as adults in sticky traps placed in the head space of

grain bins. The larvae can be distributed within the bulk mass of stored commodities, but can be spatially separated in a patchy or random distribution pattern (Nansen et al., 2004a, b).

One stored oilseed crop that is particularly vulnerable to *P. interpunctella* is stored in-shell peanuts, and in the USA *P. interpunctella* is considered to be the most important insect pest in bulk peanut storages (Arthur et al., 1988; Arthur, 1989a, b, 1994, 1995). The larvae of *P. interpunctella* will not penetrate a solid pod, but enter through a crack or split in the shell, and then feed on the kernel (Arthur, 1989a, b). Studies with the organophosphate chlorpyrifos-methyl and with the pyrethroid cyfluthrin show that the amount of insecticide required to kill the wandering-phase larvae will be 10–20 times greater than the amount required to kill adult *Tribolium castaneum* (Herbst), the red flour beetle (Arthur, 1989b, 1994, 1995). Peanuts are often stored in the shell in flat storages, and infestations of *P. interpunctella* can occur within the peanut mass. Studies in these sites also indicate a patchy or random distribution, with the greatest proportion of the population in the top of the stack and on the sides of the peanut mass next to the walls of the warehouse (Keever et al., 1985). Other fruit and nut crops that are stored in flat warehouses can also be infested with *P. interpunctella* (Johnson et al., 1992, 1995, 2002).

In recent years, there has been more emphasis on control and distribution of *P. interpunctella* in sites other than those which are storing grain or nut commodities, and many of these studies have also shown a spatially aggregated fashion (Arbogast et al., 2000, 2002). Based upon contour mapping of pheromone-baited trap records, Campbell et al. (2002) identified hot-spots, or places in which high numbers of *P. interpunctella* were found. These were near the doorways and pallet wrapping equipment in a food processing facility. Aggregated distribution could also be due to factors such as micro-climatic suitability of certain areas within a facility, interaction with biotic factors, processing practices, presence of doors and windows, and other physical attributes of a facility. Food-bait traps indicate that there is a significant correlation between some of these factors and the spatial distribution of several stored-product beetles in food processing facilities (Trematerra and Sciarretta, 2004). Knowledge of the distribution of *P. interpunctella* based upon trap catch records in a facility can help in their management. However, the use of pheromone-baited trap catch data for estimation of absolute numbers of insects, and their consequent use in spatial analysis and management, is often inaccurate and relatively poorly understood for stored-product insects (Campbell et al., 2002).

Although *P. interpunctella* is primarily associated with stored foods and not considered to be a pest of field crops, the immediate area outside of a storage facility represents an important source of infestation (Doud and Phillips, 2000). Vick et al. (1986) and Campbell and Mullen (2004) captured high numbers of *P. interpunctella* outside a food

processing facility in pheromone-baited traps. However, if there are no commodities or products stored in a particular facility, breeding in the outdoor area surrounding the facility may be limited (Cogburn and Vick, 1981). Doud and Phillips (2000) recorded rapid reinfestation of *P. interpunctella* in a flour mill after fumigation with methyl bromide, and attributed this increase to immigration from outdoor infestations. Similarly, Roesli et al. (2003) recorded an increase in populations of several stored-product insects, including *P. interpunctella*, inside a flour mill, after heat treatment. Soderstrom et al. (1987) and Campbell and Arbogast (2004) found high *P. interpunctella* activity outdoors and speculated that these moths were originating from outdoor sources. In these and other field studies, the number of generations per year varied depending on climate, food source, and specific characteristics of storage sites. Field studies in the USA have shown only one to three generations of *P. interpunctella*, with a defined peak or peaks during the summer months (Arbogast et al., 2000; Johnson et al., 2000; Campbell et al., 2002; Campbell and Arbogast, 2004; Nansen et al., 2004c).

4. Management of *P. interpunctella*

Management of *P. interpunctella* and other stored-product pests is undergoing a rapid change from an insecticide-based system to a more integrated approach (Arthur and Phillips, 2003; White, 1992; White and Leesch, 1996). Amendments made to the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) as a result of passing of the Food Quality Protection Act (FQPA) in 1996 charged the USA Environmental Protection Agency to re-evaluate all currently registered pesticides. Some organophosphate and carbamate insecticides have been removed from the post-harvest market, while some others are under threat of removal. In addition, strains of *P. interpunctella* have developed resistance to the organophosphate malathion and several other organophosphates (Attia, 1977, 1981; Zettler et al., 1973, 1989; Zettler, 1982; Arthur et al., 1988; Sumner et al., 1988; Schaafsma, 1990; Subramanyam and Hagstrum, 1996; Arthur and Phillips, 2003). *Plodia interpunctella* has also developed resistance to the microbial insecticide *Bacillus thuringiensis* Berliner in laboratory selection studies, (Johnson et al., 1990; Van-Rie et al., 1990; McGaughey and Johnson, 1992; Subramanyam and Hagstrum, 1996; Herrero et al., 2001), but there is no direct evidence of field resistance.

Fumigation is an important management option and can control all stages of *P. interpunctella* in grain bins, elevators, warehouses, and other mass grain storage structures. Some *P. interpunctella* strains have developed low-levels of resistance to phosphine (Chaudhry, 1997; Zettler, 1982; Zettler et al., 1989), but the effect of these low levels of resistance on control failures is unknown. However, there have been no recent studies of phosphine resistance as it relates to *P. interpunctella* published in

refereed journals, possibly because of the continuing decline of researchers in stored-product entomology in general, coupled with the view that resistance surveys may have little practical application when there is a limited number of insecticides that can be used. Methyl bromide, the other commonly used fumigant in stored-product pest management, is being withdrawn in most developed countries as a result of the Montreal Protocol, an international agreement (Anonymous, 2004).

Alternative or integrated control methods are being advocated as replacements or supplements for fumigants in bulk storage and in milling and processing facilities (Arthur, 1996; Dunkel and Sears, 1998; Kawakami, 1999; Toshiyuki et al., 1999; Mbata and Phillips, 2001; Mueller, 2001; Arthur and Phillips, 2003). Sanitation, improved monitoring and surveillance, surface insecticidal treatments, crack and crevice treatments, inert dusts, modified atmospheres, and heat treatments, are all mentioned as controls for *P. interpunctella* and other stored-product insects (Arthur and Phillips, 2003). Sanitation is perceived as having an effect on insect population growth in stored-product environments (Cuperus et al., 1990; Loschiavo and Okumura, 1979; Platt et al., 1998), and may improve the effectiveness of residual insecticides (Arthur and Phillips, 2003). *Plodia interpunctella* larvae can invade packaged foods (Tsuji, 1998, 2000), and insect-resistant packaging can prevent entry of larval stages and oviposition by adults (Mullen, 1994; Mullen and Mowery, 2003; Sato et al., 2003). Larvae are susceptible to low-oxygen conditions through the use of modified atmospheres, but they can survive up to 6 days under such conditions (Locatelli et al., 2002).

The use of semiochemicals in stored-product pest management has been an important option for many years (Phillips, 1997; Jones, 1998; Phillips et al., 2000b; Cox, 2004). Semiochemicals are generally used in the form of sex pheromone lures for monitoring stored-product pests, but they have a broader potential for controlling insect populations as well. Semiochemicals can be used for mass trapping, attracting and killing, mating disruption, as repellents, and as specific behavioral stimulants or deterrents (Cox, 2004). Chemical attractants (Toth et al., 2002), repellents (Khan, 1981, 1983), mating disruptors, and sex stimulants (Brady et al., 1971; Ryne et al., 2001; Fadamiro and Baker, 2002; Nansen and Phillips, 2003, 2004) for *P. interpunctella* have been evaluated in research studies but do not receive widespread commercial use.

Biological control is another possibility for control of *P. interpunctella* in bulk grain and in milling and processing facilities (Brower et al., 1996; Schöller et al., 1997; Schöller and Flinn, 2000). Laboratory and field trials have been conducted with predatory insects and with hymenopteran parasites (Schöller and Flinn, 2000). Effective field control of *P. interpunctella* and other pyralid moths has been achieved with *Habrobracon (Bracon) hebetor* (Say) (Cline and Press, 1990; Cline et al., 1984; Press et al., 1982). Several studies indicate the presence and abundance of

parasites and predators of *P. interpunctella* in and around storage facilities (Johnson et al., 2000). Wasps of the genus *Trichogramma*, which are egg parasites of many lepidopteran pests, have also been evaluated for control of *P. interpunctella* (Brower, 1990; Schöller and Flinn, 2000; Grieshop, 2005).

Low temperature storage and heat treatment of storage facilities have potential to control *P. interpunctella* (Fields, 1992). At 10 °C, a stress is imposed on adult moths, causing an increase in adult mortality; surviving adults exhibited decreased egg production and those eggs laid had lower viability (Johnson et al., 1997). One-day-old *P. interpunctella* eggs are more tolerant of heat treatment (42–48 °C) than the 2- or 3-day-old eggs, while at cold temperatures (0–10.5 °C) the older eggs were more resistant and took longer to die (Lewthwaite et al., 1998). Heat treatment in a pilot feed mill eliminated populations of different stored-product insects, but the *P. interpunctella* population gradually increased after a few weeks (Roesli et al., 2003). This gradual increase in *P. interpunctella* numbers could have been due to immigration of *P. interpunctella* from outside (Doud and Phillips, 2000). Heat and cold treatments (Johnson and Wofford, 1991; Johnson et al., 1997) can be used in combination with other control methods such as modified atmospheres or application of a granulosis virus (Johnson et al., 2002).

Management of stored-product pests based on monitoring their spatio-temporal distribution is widely recommended for achieving sustained control. Such management practices could also help in slowing down resistance development by *P. interpunctella* to various newer chemicals that are currently being tested (Arbogast et al., 2002; Trematerra and Sciarretta, 2004). Many of the studies on the spatial distribution of *P. interpunctella* are based on pheromone-baited trap catches. In such studies, there is a chance for the traps to record high numbers of adults even though they are placed far apart from the actual source(s) of infestation because of the wandering behavior of the fifth instars in search of a pupation site, and also due to the dispersal behavior of the adult moths (Campbell and Arbogast, 2004). Also, the variation in *P. interpunctella* numbers over a period of time is related to the type of sampling method used (Hagstrum, 2000). Under these situations, when management practices are purely based on such spatial distribution data, they may not yield desirable results. Nevertheless, the relative trap catch numbers or indicative trap numbers can be used as a guide in making management decisions (Arbogast and Mankin, 1999; Arbogast et al., 2000). Food-bait traps are sometimes used in combination with pheromone-baited traps to determine the distribution of *P. interpunctella* (Cox, 2004; Trematerra and Sciarretta, 2004).

The use of natural products to control various stored-product insects, including *P. interpunctella* is an alternative to chemical treatments and fumigation (Arthur, 1996). Diatomaceous earth (DE), a natural inert dust, and Spinosad, a naturally derived insecticide, are two grain

protectants that are effective against the larvae of *P. interpunctella*. Up to 86–97% of first instar *P. interpunctella* were killed by the DE Insecto[®] applied at 500 and 1000 ppm (Subramanyam et al., 1998). Spinosad was very effective against the larvae of *P. interpunctella*; 97.6–99.6% mortality was obtained when it was applied at 1 ppm (Fang et al., 2002). A granulosis virus has also been shown to be effective against *P. interpunctella* (Vail et al., 1991; Vail and Tebbets, 1993; Boots and Begon, 1995).

To conduct quantitative tests of the effects of several control methods on *P. interpunctella*, and to evaluate their effectiveness could be labor-intensive and time consuming. However, when some basic information, such as mortality, prolongation of development period, and reduction of progeny production due to such management practices on *P. interpunctella* becomes available, simulation modeling of the population dynamics of *P. interpunctella* has the potential to provide a powerful testing platform for many of these management methods, singly or in combination with each other (Throne, 1996).

5. Summary and conclusions

The behavior of *P. interpunctella* in the presence of a food source has been described in a number of publications cited earlier. However, when food is not readily accessible, or when there are no strong olfactory cues due to packaging and other barriers, *P. interpunctella* adults may lay their eggs in the vicinity of the food source so that the emerging larvae may crawl towards the food. In the absence of ready access to food, it is possible for the adults to find oviposition sites in spillage, damaged packages, and other stored-product wastes in and around a storage facility. Studies to quantify the oviposition preferences of newly emerged adults towards such alternative sites, the maximum distance from the food source that such eggs are laid, and the viability of such eggs are critical issues in population dynamics modeling, as there could be differences in the developmental biology of progeny developing outside their normal habitats.

We have shown that fecundity, development time, and other biological parameters of *P. interpunctella* are extremely variable, depending on the specific food source that was used in a particular research study. Data are lacking for many of the commodities that are commonly infested by *P. interpunctella*, such as bird seed, pet foods, and spices. Given the lack of resources and personnel in stored-product entomology, it is neither possible nor desirable to repeat studies on each and every commodity that can be infested by *P. interpunctella*. Perhaps a more promising approach is to classify the food types in to several broader categories, based on different criteria, perhaps nutrient composition (Nansen and Phillips, 2004), and quantify the biological parameters under each broader group of such commodities. If the biological parameters do not extensively vary when reared on such criterion-based commodities, this will allow researchers make more

general assumptions to model biological processes for *P. interpunctella*.

Simulation models used to predict insect population growth and development often utilize stage-specific growth rates and mortalities (Birley, 1979; Flinn et al., 1986; Smith, 1992; Martinson and Dennehy, 1995; Throne et al., 2000). Data on the development time and mortality of individual instars of *P. interpunctella* is limited in the published literature, and estimation of development times, developmental threshold temperatures, and mortalities for the five larval instars of *P. interpunctella* could help in compartmentalized modeling of the life cycle. This will in turn allow pest managers to target the life stages that are particularly susceptible to control tactics and artificially simulate the effects of such a management practice on individual life stages. Modeling the population dynamics of stored-product insects may assist in the timing of management practices and can also act as an evaluation tool for a given management practice (Hagstrum and Flinn, 1990; Flinn and Hagstrum, 1990; Flinn et al., 1997). Models that simulate population dynamics have been described for different stored-product beetle species (Throne, 1996), and for *Cadra (Ephestia) cautella* (Walker), the almond moth, another important moth pest of stored products (Throne et al., 1998).

Several studies suggest that the population of *P. interpunctella* outside a storage facility could potentially migrate inside at the beginning of a season (Doud and Phillips, 2000; Campbell and Arbogast, 2004; Campbell and Mullen, 2004). However, there are no studies to quantify the time and spatial extent of such immigration. Dispersal is an important component of insect population dynamics. If a significant proportion of *P. interpunctella* immigration into storage facilities does occur, studies may be required to quantify the immigration into the facility and the developmental biology of *P. interpunctella* populations that are breeding outside major storage facilities. Also, most of the published studies with adult moth movements are almost exclusively done with male moths because they respond to the sex pheromones. There are almost no data on movement of adult female *P. interpunctella* in stored-product facilities.

Various aspects of the biology, behavior, and ecology of stored-product insects are influenced by their spatial distribution in different facilities, which are due to factors like different processing practices, food availability, climatic differences, and interaction among other species (Trematerra and Sciarretta, 2004). Flinn et al. (1992) simulated insect populations in grain bins by dividing the grain bins into 16 different compartments and predicting insect development in the compartments based on daily average temperature. Monitoring different spatially aggregated but independent populations of *P. interpunctella* inside a storage facility will reveal the extent to which such populations vary in their developmental biology. If significant differences exist, then different population models may be needed for a single storage facility.

There are several new avenues of research for the control of *P. interpunctella* in bulk storage, mills, and processed food warehouses. Semiochemicals have the potential to control insect populations (Phillips, 1997; Agelopoulos et al., 1999; Ryne et al., 2001; Cox, 2004; Nansen and Phillips, 2004), and semiochemicals affecting *P. interpunctella* have already been identified and/or synthesized. Sex pheromone lures are used for monitoring purposes and there is potential for using the pheromone attractant for *P. interpunctella* to disrupt mating. Other possibilities for control include the use of attracticides for control of *P. interpunctella* populations under field conditions. Insect growth regulators (IGRs) are receiving increased attention in many agricultural systems, including stored products. The IGR hydroprene limits egg hatching and larval development of *P. interpunctella* (Arbogast et al., 2002; Mohandass et al., 2006a, b). Methoprene and pyriproxifen have recently been labeled as aerosol treatments and for some surface applications, and they may also affect *P. interpunctella* in a manner similar to hydroprene. Since resistance to IGRs by different insects is already reported in the scientific literature (Dame et al., 1998; Cornel et al., 2000, 2002; Horowitz and Ishaaya, 1994; Horowitz et al., 2002), trials to find alternative chemicals with different mode(s) of action or other management methods, and their use in rotation with IGRs, will help in slowing the development of resistance by *P. interpunctella*.

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