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Low-temperature aeration to control Indianmeal moth, *Plodia interpunctella* (Hübner), in stored grain in twelve locations in the United States: a simulation study

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Abstract

Aeration management strategies were developed to control cold-acclimated and diapausing Indianmeal moth, *Plodia interpunctella* (Hübner), larvae in grain bins during winter in north- and east-central regions of the US. The application in this study focuses on corn because it is the dominant crop in these regions, but we believe that the analyses can be applied to other grains as well. Contour maps for hours below −10 °C for the months of December, January, and February were developed to help effective planning and management of aeration to control overwintering stored-grain insects. Two cumulative lethality index (CLI) models were developed to estimate mortality of laboratory-reared (diapausing without cold-acclimation) and field-collected (cold-acclimated, and diapausing with cold-acclimation) *P. interpunctella* larvae under changing temperature conditions. The CLI models were used for evaluating aeration management strategies. Simulation studies were conducted using 30 years of weather data for 12 locations in north- and east-central regions of the US to evaluate different aeration management strategies for controlling *P. interpunctella* larvae. For each strategy, temperatures of headspace air and grain in the top meter of the grain mass were simulated using an existing model for the period of December–February. The tested management strategies included no aeration, continuous aeration, and intermittent aeration by controlling fan operation. During aeration, air was pulled from the headspace downward through the grain with an airflow rate of 0.11 m^3/min-t (0.1 cfm/bu). Simulation results indicated that a fan control strategy that turned the aeration fan on when the grain temperature at 0.4-m depth was greater than the headspace-air temperature was the best strategy for managing *P. interpunctella* larvae in all tested locations. For this strategy, the CLI model indicated that 100% mortality of *P. interpunctella* larvae could be achieved at a grain depth of 0.4 m from the top grain surface in all locations. For this strategy, the aeration fan operated about 10% of the time from December to February. The average cost of electrical energy required for aeration fan operation with this strategy for all locations was 1.3 ¢/t (0.033 ¢/bu) based on an electrical energy cost of 7 ¢/kWh.

Keywords: Indianmeal moth; *Plodia interpunctella*; Stored corn; Aeration; Insect management; Cumulative lethality index

1. Introduction

The Indianmeal moth, *Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae), is one of the most serious grain-infesting insects in the US and it causes large monetary losses every year. *Plodia interpunctella* can infest a wide variety of grains, nuts, dried fruits, meals, and processed foods (Sedlacek et al., 1995) and it is one of the most important pests of stored shelled corn (*Zea mays* L.) (Abdel-Rahman et al., 1968; Barak and Harein, 1981; Storey et al., 1983). In grain bins, *P. interpunctella* resides mostly in the headspace and in the upper few inches of grain (Harein and Subramanyam, 1990; Hagstrum, 2000; Nansen et al., 2004). This pest feeds on broken kernels and on kernel germs which causes loss of germination of seeds

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(Hassan et al., 1962). In addition, *P. interpunctella* contaminates the grain with silken webs and frass which may increase the resistance to airflow (Hamid, 1990) and make the grain unfit for human or animal consumption (Abdel-Rahman et al., 1968). Furthermore, *P. interpunctella* transmits spores of storage molds to grains (Abdel-Rahman et al., 1968).

In early fall, decreasing day length triggers behavioral changes in late instar (mature) *P. interpunctella* larvae (Bell, 1976). Bins tend to be poorly sealed, which allows light into the headspace and allows the insects to sense day length. Therefore, each larva spins a protective cocoon around itself that it attaches to a bin wall, ceiling, brace or within the top layers of grain, and enters diapause (i.e., a state of arrested development or hibernation) (Tzanakakis, 1959; Bell et al., 1979; Naeemullah et al., 1999). Diapausing larvae can survive long periods of cold and can spend 6 or more months in diapause depending upon the photoperiod and temperature (Bell, 1976; Bell, 1982). Diapause is terminated in late spring, when larvae resume development and the life cycle is continued.

Plodia interpunctella has been controlled using chemicals (e.g., fumigants and inert dusts) and biological control, but these methods may have serious drawbacks. Inert dusts are disliked by industry, as they contribute to abrasion of machinery and reduce market value of the commodity (Banks and Fields, 1995). Biological control has great potential for pest management, but is not yet widely used. *Bacillus thuringiensis* Berliner (*Bt*), the best-known biocontrol agent, is effective, but resistance to *Bt* in *P. interpunctella* has been reported (McGaughey and Beeman, 1988; Johnson et al., 1990). At present, fumigation with phosphine is the most common management tool for stored-product pests; however, potential for resistance to phosphine in *P. interpunctella* has been reported (Zettler et al., 1989). In addition, changes to fumigation regulations are in progress and fumigant use is expected to decline (Kells et al., 2001).

A reliable stored-grain management technique has not been developed to control cold-acclimated and diapausing *P. interpunctella* larvae. The use of cold ambient air occurring in fall and winter seasons to control stored-grain insects has been investigated in different parts of the world (Epperly et al., 1987; Lasseran and Fleurat-Lessard, 1990; Hagstrum and Flinn, 1994; Longstaff, 1994; Fields and White, 1997). The use of low temperatures to control stored-grain insects is becoming an attractive control method among the non-chemical insect-control methods (Fields, 1992; Longstaff, 1994; Arthur and Johnson, 1995; Maier et al., 1997; Wilcke and Cannon, 2002). Furthermore, fall and winter aeration with ambient air is recommended to reduce grain deterioration and maintain grain quality (Cloud and Morey, 1980; Wilcke and Morey, 1999; Bennett and Brown, 2000; Kawamura et al., 2001). Insect activity slows if the temperature is reduced to below developmental thresholds and insects die if exposed to low temperatures for a long enough time (David et al., 1977; Evans, 1987; Fields, 1992; Hagstrum and Flinn, 1994).

Cold tolerance in insects is often related to their supercooling points. The supercooling point (SCP) is defined as the temperature at which spontaneous freezing occurs as indicated by the release of the latent heat of fusion when the insect is cooled at a cooling rate of $1\,^{\circ}\mathrm{C\,min^{-1}}$ (Renault et al., 2002). In freeze-intolerant insects such as *P. interpunctella* (Lee et al., 1992; Naeemullah et al., 1999), the SCP represents the limit of low-temperature tolerance and freeze-intolerant insects die upon freezing. However, cold injuries and death can occur at temperatures above this point (Bale, 1987). Most stored-product insects have SCPs from −20 to −10 °C (Fields, 1992).

Lee et al. (1992) found that the SCP of *P. interpunctella* larvae reared at 23 °C was −10.3 °C. Naeemullah et al. (1999) reported that the SCPs of diapausing and non-diapausing larvae of *P. interpunctella* reared at 20 and 25 °C ranged from −15 to −12 °C. They also observed a 100% mortality of both diapausing and non-diapausing larvae after an 8-h exposure to −10 °C, and less than 1-h exposure to −20 °C. Dohino et al. (1999) found that an exposure of 1.5 or 2 h to −18 °C completely killed all stages of laboratory-reared *P. interpunctella* (i.e., eggs, all ages of larvae, pupae, and adults). *Plodia interpunctella* larvae from field and laboratory colonies originating from California, Florida, Indiana, Minnesota, Oklahoma, and Texas were found to have a mean SCP ranging from about −20 to −13 °C (Carrillo and Cannon, 2005).

Local weather information such as mean number of hours below critical threshold temperatures of stored-grain insects at different periods of the year can be obtained by analyzing historical weather records (Arthur et al., 1998, 2001). This type of weather information is useful for developing management strategies to control stored-grain insects (Arthur et al., 1998, 2001; Wilcke and Cannon, 2002). In addition, mathematical models based on physical principles can help test the effectiveness of proposed insect-control management strategies (Flinn and Hagstrum, 1990; Maier et al., 1996).

Despite relatively low temperatures during much of the year in north- and east-central regions of the US, insect problems in stored grain in these regions have been documented by several stored-grain surveys (e.g., Storey et al., 1983). The most commonly found moth species in these regions is *P. interpunctella*. *Plodia interpunctella* is thought to be one of the most cold-hardy stored-product pests (Howe, 1965; Fields, 1992). However, it is not found in grain bins in the Canadian Prairies—the coldest grain-growing region in North America (Yaciuk et al., 1975; Madrid et al., 1990; Fields, 1992). One explanation is that winter temperature extremes in these regions exceed the cold tolerance limits of *P. interpunctella*. Because several parts of the north- and east-central regions of the US have cold weather, temperature manipulation in grain bins during fall and winter seasons might offer an alternative