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Investigation of fumigant efficacy in flour mills under real-world fumigation conditions

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ABSTRACT

Fumigation experiments under laboratory conditions are common but due to a number of factors, fumigation experiments under real-world conditions are difficult and rare. This study was aimed at providing an insight into efficacy evaluations of fumigants based on insect mortality data under real-world conditions. A total of eight sulfuryl fluoride (SF) and three methyl bromide (MB) fumigations were performed in four different flour mills in the Midwestern United States. Bioassays were undertaken with all insect life stages (i.e., eggs, larvae, pupae and adults) of *Tribolium castaneum* (Herbst) and *Plodia interpunctella* (Hübner) placed inside fumigated structures. In addition, in most of the fumigations, environmental conditions (e.g., prevailing wind, temperature, and relative humidity) and gas concentrations were monitored. Complete mortality was obtained for the adults and larvae of both insect species, and for the pupae of *P. interpunctella*. Some *T. castaneum* pupae survived in all three MB fumigations and in one SF fumigation. In addition, some exposed eggs were able to reach the adult stage in one MB and four SF fumigations. The methodology and procedures presented can be used in future field studies of fumigant efficacy.

1. Introduction

For many years, methyl bromide (MB) has been the major fumigant used worldwide for quarantine treatments, for the control of structural pests and pests in commodities due to its fast reaction and versatility (Taylor, 1994). Currently, MB is being phased-out globally because it is an ozone-depleting substance according to the Montreal Protocol. For developed and developing countries, 100% phase-out of MB as a structural treatment was scheduled to be completed by 2005 and 2015 respectively (UNEP, 2007), but usage persists in developed countries through Continuing Use Exemptions (CUEs). Since the early 1960s, sulfuryl fluoride (SF) has been used as a non-food structural fumigant to control drywood termites and other wood-infesting insects (Stewart, 1957; Derrick et al., 1990). Studies have been conducted to evaluate the efficacy of SF against stored-product insects as an MB replacement (Drinkall et al., 1996; Bell and Savvidou, 1999; Bell et al., 1999, 2003, 2004; Reichmuth et al., 1999; Schneider and Hartsell, 1999; Wontner-Smith, 2005), and also establishing mortality dosages (i.e., concentration × time or Ct products). SF was first approved for fumigation of food processing facilities in Switzerland in June 2003 under the trade name ProFume® (Drinkall et al., 2004) and approvals have now been granted in many other countries (for example, Australia, Canada, France, Germany, Italy, United Kingdom, and United States).

Since SF is an inorganic compound, it does not bind onto organic materials, making it a potentially better penetrator than MB, which is an organic compound (USDA ARS, 2000). Sorption of SF in wood and flour is substantially less than that of MB (Scheffrahn et al., 1992), but SF penetrates through nylon and polyethylene sheeting more slowly (U.S. EPA, 2006). Comparison studies between MB and SF on insect population reduction and rebound have been conducted using pre- and post-fumigation trapping data. Campbell et al. (2004) and Hou et al. (2007) found that the insect capture data may be affected by other variables such as temperature variation, degree of insect movement, and level of sanitation. Small (2007) found no significant difference between the recovery of stored-product beetle or stored-product moth populations in mills fumigated with SF or MB. However, for fumigation in food processing structures, research publications that provide real-world (not laboratory) fumigant efficacy evaluations based on mortality

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data are limited in the literature. In most publications, such research has been conducted mostly for SF and been based on one to three fumigation trials (Drinkall et al., 2003, 2004; Reichmuth et al., 2003; Bell et al., 2004; Small, 2007). Difficulties in conducting this type of experiment include high cost, limited access to commercial facilities and fumigation companies, variations in weather conditions and differing fumigation practices between experiments, etc. In the present study, a total of eight SF and three MB fumigations were performed in four commercial flour mills in collaboration with professional fumigators. This study was done to evaluate fumigant efficacy under real-world conditions.

2. Materials and methods

2.1. Flour mills

Four flour mills (A, B, C, and D) located in the Midwestern United States were selected for this study (Table 1). These facilities consist of several connecting structures (e.g., a flour mill, truck and railcar load-out stations, warehouse, packaging area, grain bulk storage structure, and maintenance building). The flour mill sections were the main focus of this study. Within each mill, floors are interconnected by various types of openings such as stairwells, manlifts, piping and ducting, allowing air to circulate between floors. Openings typically run through the mill from the top through to the bottom floors. Mills A and D are relatively new structures and constructed of pre-cast concrete and cast-in-place concrete, respectively. Mill B is a combination of brick walls and wooden floors. Mill C is mostly a brick structure with a combination of wooden and concrete floors. Thus, the air-tightness of Mills A and D is, in general, better than that of Mills B and C as can be seen in the leakage rates (half-loss time) observed during the fumigations (Table 3).

2.2. Fumigation practices

The fumigations conducted in this study were part of the regular insect control measures of the flour mills. Prior to each fumigation, the structure was thoroughly cleaned and sealed following typical commercial fumigation protocols. All fumigations were undertaken between the months of April and October 2005–2007. Exposure period was defined as the time between the first release of the fumigant and the start of unsealing. For most fumigations, the fumigant introduction points and circulation fans were distributed throughout the structures such that proper gas distribution was obtained, and the exposure periods lasted more than 20 h (Table 2). The amount of fumigant (i.e., mass) used can be divided into initial and top-up releases. The initial release was the total fumigant amount that was introduced into the structure within the first 2 h of the fumigation and the top-up releases were subsequent injections over the remaining hours for the purpose of achieving the target Ct product. For each SF fumigation, as mandated by the product label (Dow AgroSciences, 2005), the amount of fumigant used was determined using the Fumiguide™ fumigation management software (Dow AgroSciences, Indianapolis, IN, USA) which takes into account various fumigation conditions such as estimated leakage rates (i.e., half-loss time or HLT), exposure durations, volumes being treated, and target pests. The dosage rate of MB according to the product label (Great Lakes Chemical, 1994) specifies a range that fumigators should achieve (i.e., 16–48 g/m^3 with 16–24 h of exposure time) and fumigators typically attempt to achieve a minimum Ct product value based on their experiences.

2.3. Environmental condition and gas concentration measurements

Intensive environmental monitoring and gas concentration measurements were conducted only in three mills, Mills A, B and D. The instrumentation setup for monitoring environmental conditions and gas concentrations for the fumigations in all flour mills was similar. A temperature/relative humidity (r.h.) logger (Hobo H8 family, Onset Computer Corporation, Bourne, MA) was placed near the center of each floor to obtain the temperature and r.h. profiles of the gas along the height of the mill. These temperature and r.h. data were collected every 4 min. To monitor the outside weather conditions, a Hobo weather station (Onset Computer Corporation, Bourne, MA) was set up on the roof of the mill building at the highest location available. It monitored wind speed and direction, temperature, and r.h. with a sampling interval of 1 min. Vinyl tubes (4.3 mm inner diameter) were used to draw gas samples from inside the mill to the outside monitoring station. The total number of fumigant monitoring lines varied between 11 and 20 (Table 2). Monitoring lines were distributed throughout the mill. At least one line was placed on each floor of the mill. Concentration measurements were made in cycles through all monitoring lines using either a Fumiscope® (Key Chemical and Equipment Co., Clearwater, FL) or Spectros Instruments Single Zone Monitor (Spectros Instruments Inc., Hopedale, MA). Each gas reading required three to 5 min, resulting in 30–60 min sampling cycles.

Due to limited access to Mill C, environmental conditions both inside and outside the mill were not monitored and gas concentration monitoring was not as intensive as in the other three mills in terms of both monitoring points and frequency. For Mill C MB fumigations, fumigant concentrations were monitored at only three locations at 1 h intervals. Mill C SF gas concentrations were monitored at 12 locations at 3 h intervals. For comparative purposes, ambient weather data from a nearby airport during Mill C fumigations were obtained from the Indiana State Climate Office's website (http://climate.agry.purdue.edu/climate/).

2.4. Insect bioassays

Tribolium castaneum (Herbst) stock colonies were maintained on a flour/yeast diet (90% flour and 10% brewers' yeast) in glass jars (800 ml) sealed with a double layer of filter paper for a lid. Colonies were maintained at 30 ± 0.5 °C, 72% r.h. To determine the fumigation efficacy, bioassay trays containing all life stages of *T. castaneum* were placed within the structure during the fumigation. The following age *T. castaneum* life stages were prepared for bioassay: adults 7–14-d post eclosion; 1–2-d old pupae; 3rd and 4th instar larvae; and 2-d old eggs. A No. 25-mesh sieve (Seedburo Equipment Company, Chicago, IL) was used to collect adults, larvae and pupae,

Table 1
Estimated volumes and structural details of flour mills.

Mill	Total volume[a] (m^3)	Mill volume[b] (m^3)	# of floors	Basement	Structure material	Approximate age (y)
A	60,000	30,200	6	No	pre-cast concrete	15
B	14,500	6500	6	Yes	brick and wood	120
C	27,500	19,600	10	Yes	brick, wood and concrete	100
D	6200	4700	6	Yes	cast-in-place concrete	65

[a] The total volume includes the volumes of all connecting structures in the facility.
[b] Fumigated structure.